Cyntia Bailer

THE NEURAL PROCESSING OF SENTENCES IN BILINGUALS AND MONOLINGUALS: AN FMRI STUDY OF PORTUGUESE-ENGLISH BILINGUALS AND PORTUGUESE MONOLINGUALS READING COMPREHENSION EFFECTS ON BRAIN ACTIVATION

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Orientadora: Profa. Dra. Lêda Maria Braga Tomitch

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Esta Tese foi julgada adequada para obtenção do Título de "Doutor em Estudos da Linguagem" e aprovada em sua forma final pelo Programa de Pós-Graduação em Inglês.

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To my family
With all my love

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I do not know what I may appear to the world, but to myself I seem to have been only like a boy playing on the sea-shore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me.

(Isaac Newton, 1855)

(in Memoirs of the Life, Writings, and Discoveries of Sir Isaac Newton by Sir David Brewster (Vol. II, Ch. 27).

ABSTRACT

Although considerable research has been devoted to language representation and processing in monolinguals, rather less attention has been paid to language representation and processing in bilinguals and even less, to the comparison in brain activation between bilinguals and monolinguals reading in their L1. Since the majority of studies on bilingualism investigate processes at the word level, the present dissertation, a cross-sectional, quantitative and exploratory study in nature, aimed at investigating monolingual and bilingual brains and their neuroanatomical response to the processing of written sentences. More specifically, it sought to explore (1) whether and to what extent Portuguese and English are represented and processed in the same areas of the brain in late bilinguals; (2) whether Portuguese is represented and processed in same brain areas in bilinguals and monolinguals; (3) whether the semantic neural representation of sentences in one language can be identified based on the brain activation for the same sentences in another language; (4) whether individual differences, namely proficiency in the second language and working memory capacity, modulate activation in bilinguals, whether working memory capacity modulate activation in monolinguals; and (5), whether word length and lexical frequency have an effect on brain activation. Twelve Brazilian Portuguese-English late bilinguals and ten Brazilian Portuguese monolinguals participated in the study. Data collection took place at *Carnegie Mellon University* during a PhD internship. The stimuli consisted of 60 sentences in English and their translation-equivalent sentences in Portuguese (e.g., *The diplomat negotiated at the embassy/O diplomata negociou na embaixada*). Bilingual participants read the sentences while functional images were acquired on two separate days while monolinguals only read the Portuguese sentences in a single session. Data were analyzed statistically and revealed, in general terms, that language representation and processing engages a complex network of brain areas in monolinguals and bilinguals. For processing the L2, bilinguals recruit a more widely distributed set of areas bilaterally than for processing the L1 (more left-lateralized). For processing the L1, in comparison with monolinguals, bilinguals recruited additional bilateral areas for dealing with the phonological and semantic aspects of the L1. In spite of the small differences in processing the languages, the commonalities in concept representations across languages were sufficient to allow decoding of sentences using multi-voxel pattern analysis and machine learning techniques. The model generated reasonable accurate predictions of the neural representation of words in the context of sentences based on simple addition of words, semantic features and semantic cuboids derived from an independent study. Variables as proficiency in the L2, working memory capacity, word length and lexical frequency modulated brain activation. In a nutshell, findings add support to the literature about bilingual and monolingual language comprehension and contribute to the area by suggesting that there are common neural areas involved in the representation of different languages and cultures.

Keywords: bilingualism; Portuguese-English bilinguals; Portuguese monolinguals; L1; L2; reading comprehension; fMRI; language processing; language representation.
Number of pages: 204 (224 with references)
Number of words: 61,666

RESUMO

Embora um considerável número de pesquisas tem se dedicado à representação e ao processamento da linguagem em monolíngues, menos atenção tem sido dada à representação e ao processamento da linguagem em bilíngues e ainda menos, à comparação da ativação cerebral de bilíngues e monolíngues ao ler sua L1. Já que a maioria dos estudos sobre bilinguismo investigam processos no nível da palavra, a presente tese, um estudo de natureza transversal, quantitativa e exploratória, objetivou investigar cérebros de monolíngues e bilíngues e sua resposta neuroanatômica ao processamento de frases escritas. Mais especificamente, procurou explorar (1) se as duas línguas, português e inglês, são representadas e processadas nas mesmas áreas do cérebro de bilíngues tardios e em que medida; (2) se a L1 (português) é representada e processada nas mesmas áreas cerebrais de bilíngues e monolíngues; (3) se a representação neural semântica de frases em uma língua pode ser identificada baseada na ativação cerebral das mesmas frases na outra língua; (4) se diferenças individuais como a proficiência na segunda língua e a capacidade de memória de trabalho modulam a ativação em bilíngues e se a capacidade de memória de trabalho modula a ativação em monolíngues; e (5) se a extensão das palavras e a frequência lexical têm efeito na ativação cerebral. Doze bilíngues tardios do par linguístico português brasileiro-inglês e 10 monolíngues do português brasileiro participaram do estudo. Os dados foram coletados na *Carnegie Mellon University* durante o doutorado sanduíche. Os estímulos consistiram de 60 frases em inglês e frases equivalentes em português (ex.: *The diplomat negotiated at the embassy*/*O diplomata negociou na embaixada*). Os participantes bilíngues leram as frases enquanto imagens funcionais do cérebro eram adquiridas em dois dias distintos enquanto os participantes monolíngues apenas leram as frases em português numa única sessão. Os dados foram analisados estatisticamente e revelam, em termos gerais, que a representação e o processamento da linguagem engaja uma rede complexa de áreas cerebrais em monolíngues e bilíngues. Para processar a L2, os bilíngues recrutam um conjunto mais amplamente distribuído de áreas bilaterais que para processar a L1 (mais lateralizada à esquerda). Para processar a L1, em comparação com os monolíngues, os bilíngues recrutaram áreas adicionais bilateralmente para lidar com os aspectos fonológicos e semânticos da L1. Apesar das pequenas diferenças no processamento das línguas, as semelhanças na representação dos conceitos entre as línguas foram suficientes para permitir a decodificação de frases usando técnicas de aprendizagem de máquina e de análise de padrão *multi-voxel*. O modelo gerou predições razoavelmente precisas da representação neural de palavras no contexto de frases baseado na adição simples de palavras, características semânticas e cuboides semânticos derivados de um estudo independente. Variáveis como a proficiência na L2, a capacidade de memória de trabalho, a extensão das palavras, e a frequência lexical influenciaram a ativação cerebral. Em suma, os achados corroboram a literatura sobre compreensão de linguagem em monolíngues e bilíngues e contribuem com a área ao sugerir que há áreas neurais comuns envolvidas na representação de diferentes línguas e culturas.

Palavras-chave: bilinguismo; bilíngues do par linguístico português-inglês; monolíngues do português; L1; L2; compreensão de leitura; ressonância magnética funcional; processamento de linguagem; representação de linguagem.
Número de páginas: 204 (224 com referências)
Número de palavras: 61.666

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LIST OF ACRONYMS

AAL - Anatomical Automatic Labeling
AFRL - *Air Force Research Laboratory*
AoA - Age of Acquisition
ATL - Anterior Temporal Lobe
BA - Brodmann Area
BIA - Bilingual Interactive Activation model
BOLD effect - Blood Oxygenation Level Dependent effect
CAPES - Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (Coordination for the Improvement of Higher Education Personnel)
CCA - Canonical Correlation Analysis
CCBI - *Center for Cognitive Brain Imaging* at *Carnegie Mellon University*
DLPFC - Dorsolateral Prefrontal Cortex
DTI - Diffusion-Tensor Imaging
EPI - Echo Planar Imaging
ERPs - Event-Related Potentials
fMRI - functional Magnetic Resonance Imaging
FTP - File Transfer Protocol
FWER - Family-Wise Error Rate
GLM - General Linear Model
GNB - Gaussian Naïve Bayes classifier
IARPA - *Intelligence Advanced Research Projects Activity*
IELTS - International English Language Testing System
IFG - Inferior Frontal Gyrus
IPS - Intra-Parietal Sulcus
IRB - Institutional Review Board
L1 - first language, mother tongue
L2 - second language
LCD - Liquid Crystal Display
LH - Left Hemisphere
LTM - Long-Term Memory
M - mean
MEG - Magnetoencephalography
MNI - Montreal Neurological Institute
MPSC - Mean Percent Signal Change
MRI - Magnetic Resonance Imaging
MTG - Middle Temporal Gyrus
MVPA - Multi-Voxel Pattern Analysis

ODNI - *Office of the Director of National Intelligence*
PET - Positron Emission Tomography
PFC - Prefrontal Cortex
PPGI - Programa de Pós-Graduação em Inglês da UFSC
PSC - Percent Signal Change
RH - Right Hemisphere
RHM - Revised Hierarchical Model
RST - Reading Span Test
SD - Standard deviation
SIBR - *Scientific Imaging & Brain Research Center* at *Carnegie Mellon University*
SMA - Supplementary Motor Area
SPECT - Single Photon Emission Computer Tomography
SPM8 - 8th version of the software named Statistical Parametric Mapping
STG - Superior Temporal Gyrus
T - Tesla
TE - Echo Time
TMS - Transcranial Magnetic Stimulation
TOEFL - Test of English as a Foreign Language
TR - Repetition Time
VWFA - Visual Word Form Area
WM - Working Memory
WMC - Working Memory Capacity

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CHAPTER 1
INTRODUCTION

Language is an instrument for conveying meaning. The structure of this instrument reflects its function, and it can only be properly understood in terms of its function. To study language without reference to meaning is like studying road signs from the point of view of their physical properties (how much they weigh, what kind of paint are they painted with, and so on), or like studying the structure of the eye without any reference to seeing. (Wierzbicka, 1996, p.3)

1.1 PRELIMINARIES

The ability to understand and speak a language has been taken as the *sine qua non* of human cognition. It has been fascinating several research communities: Linguistics, Psychology, and Computer Science and subareas such as Psycholinguistics and Cognitive Psychology. Innumerous aspects related to language production and comprehension have been investigated. In this context, it is commonsensical that human languages are symbolic systems that have been evolving for thousands of years and serve various functions in communication. Evolutionarily, speaking seems to be as old as humankind, whereas reading and writing may be considered a cultural invention (Dehaene, 2009).

Language comprehension depends, first, on understanding the meaning of individual words, so that we are able to understand the relationship between words in a sentence, in a paragraph, in discourse as whole. At this very moment, while you are reading these pages, your brain is accomplishing a fascinating feat. Your eyes scan the page in short twitching movements. Your gaze moves around the page constantly. Four or five times per second, your gaze lands on a word or two (Dehaene, 2009). The fovea, the center of the retina in your eyes, with its excellent resolution, allows for the recognition of written input (Just & Carpenter, 1980). This process is so automatized in fluent readers that we are not attentive to the process; we take for granted our ability to read as we do not commonly think of what reading entails. We are normally only conscious of the sounds and the meanings that reach our conscious minds.

The reader's brain consists of a complex set of mechanisms excellently adjusted to reading. With the advent of new methods, researchers have started to disentangle the principles underlying the brain's cognitive circuits. Neuroimaging techniques are capable of revealing, in a speed never thought before, the brain areas that *light up* when we read. Such areas, in conjunction with theoretical models and behavioral evidence, help us understand what reading is all about. In addition to reading, these techniques may elucidate what happens in the brain when we learn a new language, when we are processing written input in such a new language. To be able to learn a new language, the brain dynamically adapts. No matter at what age, individuals have the ability to learn, decode input and communicate in a new language. Such ability relies on cognition, "the characteristically dynamic and resourceful human act or process of knowing" (Buchweitz, 2006, p.1).

Naturally, advancements entail interdisciplinary efforts and partnerships. The present study is an outcome of such efforts and partnerships. As the brain cannot accomplish a task with a single neuron or a single brain region, this study would not have been possible without the cooperation, organization and resourcefulness of professors Lêda Tomitch and Marcel Just.

1.2 STATEMENT OF PURPOSE: THE INVESTIGATION OF BRAIN ACTIVATION FOR READING COMPREHENSION IN BILINGUALS AND MONOLINGUALS

Modern-day communication has not been restricted to countries' boundaries. Besides face-to-face, individuals can communicate through new ways; as traveling has become easier, faster and more affordable than before. Such widespread communication has intensified the significance of being able to communicate in and understand more than one language. Grosjean (2012) claims that "there are probably more bilinguals on the earth today than monolinguals and that, in this age of global communication and travel, the number will surely increase" (p.243).

Behavioral and neuroimaging studies of bilinguals have been pervaded with controversy. Such controversy emerges from a variety of factors: different definitions of bilingualism, different characteristics of languages, different research methods and tasks. Most researchers agree that bilinguals are those individuals who use two or more languages in their everyday lives (Grosjean, 2012). However, a number of features influences such definition. People acquire and use languages for different purposes, in different domains of life, at different ages, with different people. Bilinguals may be in the process of acquiring the language or may have reached a certain level of stability. As well, the language repertoire may change over time. In research reports, the information given about participants is sometimes merely insufficient to picture who the participants are and to understand their realities (Grosjean, 1998).

Languages vary in terms of writing systems, structure, mapping of written symbols to sound, morphology, syntax, among many other characteristics. Methods, stimuli and tasks employed in studies also vary. As neuroimaging techniques are thought to provide a window into the brain (Ferstl, 2007), researchers make use of tools such as Functional Magnetic Resonance Imaging (fMRI), Positron Emission Tomography (PET), Transcranial Magnetic Stimulation (TMS) as well as stimuli presented visually and/or aurally with the objective of *watching the brain at work*. As tasks, the most common ones are: semantic decision and categorization (Illes et al., 1999; Isel, Baumgaertner, Thrän, Meisel & Büchel, 2010), picture naming (Parker Jones et al., 2012), syntactic and semantic judgments (Wartenburger et al., 2003; Saur et al., 2009), silent reading (Yang, Tan & Li, 2011; Jamal, Piche, Napoliello, Perfetti & Eden, 2012), and comprehension probes (Nakada, Fujii & Kwee, 2001; Hasegawa, Carpenter & Just, 2002), to mention some. As it will be scrutinized in the review of literature chapter, some studies examine the brain representation of concrete nouns (Buchweitz, Shinkareva, Mason, Mitchell & Just, 2012); others investigate the processing of active vs. passive sentences (Yokoyama et al., 2006). Some explore the effect of individual differences such as working memory (Buchweitz, Mason, Tomitch & Just, 2009a), proficiency (Kim, Relkin, Lee & Hirsch, 1997; Tatsuno & Sakai, 2005; Meschyan & Hernandez, 2006) and age of acquisition (Hernandez, Woods & Bradley, 2015), others, language switching (Hernandez, Dapretto, Mazziotta & Bookheimer, 2001) and control (Crinion et al., 2006). Some study the effect of orthography (Chee et al., 1999; Buchweitz, Mason, Hasegawa & Just, 2009b) others, the effects of modality of presentation (Buchweitz et al., 2009a), and others, more recently, the semantic neural identification of words (Buchweitz et al., 2012; Correia et al., 2014). The majority of studies investigate processes at the word level; few studies explore the sentence level, and even fewer studies, the level of discourse.

All these differences fuel controversy in the comparison of results. Although these factors seem to contradict one another, "they do help piece together the puzzle of neural mechanisms involved in bilingual comprehension and cognition" (Buchweitz, 2006, p.137). Theoretical models based on behavioral evidence obtained with monolinguals were adapted to the bilingual population, and even though a great number of studies agree that bilinguals have a shared meaning representation system, some issues are unclear. For instance, the extent to which bilinguals employ the same brain areas for the processing of L1 and L2[1], the degree of overlap and the degree of difference, and what factors influence the representation of languages in the bilingual brain are suggested topics (Marian, Spivey & Hirsch, 2003). As well, neuroimaging studies have not focused their attention on the direct study of language processing in the brains of bilinguals compared to monolinguals.

The majority of studies in the bilingual literature have investigated language at the word level (Van Assche, Duyck & Brysbaert, 2012). Comprehension of natural language, in the context of sentences, paragraphs, stories, conversations, larger pieces of text are very complex (Jung-Beeman, 2005) to be explored with neuroimaging techniques. Because scholars conjecture that the processing of words in context may be different from the processing of words in isolation, the field calls for more studies within the limitations of neuroimaging techniques.

Based on the above, the objective of the present dissertation is to investigate monolingual and bilingual brains and their neuroanatomical response to the processing of written sentences. More specifically, (1) it seeks to explore whether and to what extent Portuguese and English are represented and processed in the same areas of the brain in late bilinguals; (2) whether Portuguese is represented and processed in same brain areas in bilinguals and monolinguals; (3) whether the semantic neural representation of sentences in one language can be identified based on the brain activation for the same sentences in another language; (4) whether individual differences, namely proficiency in the second language and working memory capacity modulate activation in bilinguals and whether working memory capacity modulate activation in

[1]L1 is used in this study to refer to the mother tongue, or the first language learnt by an individual. L2 is used to refer to the second language of an individual. It is essential to highlight that the term L2 is used in this study to refer to the languages both learnt in a foreign environment (e.g.: Brazilians learning English in Brazil) and in the context of the language (e.g.: Brazilians learning English in the US).

monolinguals; and (5), whether word length and lexical frequency have an effect on brain activation. The aim is to investigate the brain response to sentence comprehension proper. Bilinguals in this study had no other instruction but to understand the sentences by creating a meaningful mental representation and to think about the meaning of the sentences consistently across presentations.

In a nutshell, the present study is inserted in the context of language, particularly reading, comprehension research and teaching at the university level. In addition to being inserted in *UFSC*'s context, the study was carried out in the U.S. at the *Center for Cognitive Brain Imaging* at *Carnegie Mellon University* thanks to the PhD internship offered by CAPES and Dr. Just's acceptance. Therefore, this study is also inserted in that laboratory's research interests in exploring higher-level cognitive processes involved in language comprehension and human cognition[2]. The cooperation of interests at my home university and the university abroad permitted the application of a modern neuroimaging tool to collect data of the brain at work. Additionally, the experiment reported in this work is inserted in the context of multidisciplinary scientific work conducted at the foreign institution. I hope the results can benefit both communities as well as broaden the limits of investigation with Brazilian Portuguese monolinguals and bilinguals (English as an L2).

1.3 FMRI: A TOOL TO STUDY THE BRAIN AT WORK

In this subsection, I provide the reader with some of the basics of functional magnetic resonance imaging (fMRI) and its contributions to the study of language processes. As well, I provide the reader with some information about the brain, its divisions, and how studies report their imaging results. For a more in-depth review about the tool, the reader is referred to Huettel, Song, and McCarthy (2009).

According to Bookheimer (2002), functional brain imaging has "revolutionized the study of language" (p.151). Although it may sound

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[2]Due to the high costs of conducting fMRI experiments, the present study was possibly thanks to the funding provided by the *Office of the Director of National Intelligence* (ODNI), *Intelligence Advanced Research Projects Activity* (IARPA), via *Air Force Research Laboratory* (AFRL) contract number FA8650-13-C-7360. The present study is part of greater project called KRNS (Knowledge Representation in Neural Systems) and funding was provided to Dr. Marcel Just and his colleagues at Carnegie Mellon University.

as an overstatement, such technique has enabled us to see the healthy brain as well as the atypical brain at work. More than 150 years of research into the organization of language in the human brain was based on the lesion-deficit approach. It is used to understand the consequences of a variety of neural illness, such as stroke, epilepsy, Alzheimer's disease, to mention some. The assumption in this approach is that if a person suffers from brain damage and loses the capacity to do certain things, it may be possible to infer that the lost function depends on the damaged structures. Thus, neuropsychological studies provide information about the necessity of particular brain areas for lost cognitive functions (Price, 1998).

Paul Broca and Carl Wernicke in the 1800's, using a scalpel and their clinical notes, have identified two important brain regions for language: the left inferior frontal area and the posterior superior temporal region, respectively. If damaged, the former, Broca's area, results in impaired speech production and relatively intact comprehension of words. Wernicke's area, the latter, if damaged, results in impaired speech perception with relatively fluent speech production. Kandel, Schwartz and Jessell (2000) suggest that we should think of higher mental processes "as several railroad lines that all feed into the same terminal" (p.15-16); the breakdown of a single link on one way disrupts how the information is carried by that way, but does not necessarily interfere with the system as a whole. They explain that it is the reason why it is so hard to describe effectively how higher mental processes are implemented in the brain.

Price (1998) and Ullman (2006) point out a number of disadvantages of lesion studies: (1) brain lesions involve multiple and, sometimes, large brain structures; (2) losing a function following a lesion does not detect the other regions necessary for that function; (3) a language deficit can appear because other critical areas have been directly or indirectly disconnected; (4) with time, the brain can recover and adapt itself to perform some 'lost' functions; and (5) each case has its specificities. Consequently, findings from this technique cannot not be generalized to the healthy population.

The availability of neuroimaging techniques[3] has enabled

[3]Such as fMRI, PET (Positron Emission Tomography), SPECT (Single Photon Emission Computer Tomography) and MEG (Magnetoencephalography). ERPs (Event-related Potentials) provide the researcher with the electrical activity of the brain, the reason why some researchers do not consider them as neuroimaging. PET and SPECT involve the injection of radioactive tracers in

researchers to measure brain activity during the execution of tasks both in healthy and impaired individuals. fMRI is “by far the most widely used neuroimaging method today” (Ullman, 2006, p.249) due to its availability, flexibility, high spatial resolution, relatively good temporal resolution, and lack of radiation or need for contrast injection (Amaro Jr. & Barker, 2006). It captures the brain hemodynamics: changes in the blood stream – such as increases in blood flow and changes in the oxygen level – occur when neurons increase their firing rate. In other words, it detects changes in the oxygenation of blood flow that occur in response to neural activity - when one area of the brain is more active, it consumes more oxygen and to deal with this demand, it is possible to observe an increase in blood flow in the activated area. The fMRI method may be used with patients and healthy subjects to study higher cognition, for instance, to investigate the areas involved in mental processes, in language production and comprehension[4], in conceptual categorization as well as the functional and structural connectivity of networks at high spatial resolution (Huettel et al., 2009; Mitchell et al., 2004; Sakai, 2005). Such technique is able to reveal the brain areas that are involved in, and yet not necessarily crucial to, the performance of a task.

Data collection using fMRI happens in a special room with an MRI machine inside. It employs strong magnetic fields to generate images of biological tissue. The strength of the magnetic field created by an MRI scanner is expressed in Tesla (T), and available scanners have field strengths of 1.5 T to 7 T (Huettel et al., 2009). The one used in this study, a 3 T scanner, is approximately 60,000 times stronger than the Earth’s magnetic field. A typical scanner weighs from 5-10 tons and is designed to provide a high homogeneous magnetic field inside the bore where the person to be imaged is positioned (Amaro Jr. & Barker, 2006). It is known that atoms of hydrogen are very common in the brain, in water, in fat, in proteins, and because they are sensitive to magnetic forces, they line up in the magnetic field, in the same way a compass needle aligns with the earth’s magnetic field. The scanner makes use of radio waves to disturb the atoms’ alignment and records the signals they

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the blood, displaying potential health risks for the participants (Ullman, 2006). As the present study was carried out with fMRI, I chose not to review the advantages and disadvantages of those techniques, due to page limitations.

[4]Studies about language production and comprehension with fMRI have been, mostly, restricted to the investigation at the word and sentence levels, as the reader will perceive in the Review of the Literature chapter of the present work.

release while they come back to alignment in the field. Such signals are used to reconstruct an image of the brain. In a structural image, the signals of hydrogen atoms in different molecules are used to reconstruct the anatomical structures of the brain. In functional images (fMRI), researchers take advantage of changes in oxygenation level in the blood. When neurons increase their firing rate – they need oxygen and glucose for energy –, it is possible to observe an increase in oxygenated hemoglobin as compared to deoxygenated hemoglobin, as the blood brings in more oxygen. Deoxygenated hemoglobin disturbs the magnetic field while oxygenated hemoglobin does not, so, the fMRI can detect changes in the ratio between the two. This ratio is known as blood oxygenation level dependent (BOLD) effect. Since the ratio differs between regions with various amounts of neural activity, fMRI indirectly images differences in neural activity between different task conditions.

As every method, it has advantages and disadvantages. It provides great spatial resolution, but not so good temporal resolution. As the technique measures blood oxygenation, it can only capture how the neural activity increased in the preceding seconds. Dehaene (2009) cites a comparison made by his friend, who relates the method to "spying on a gardener to foresee where seeds will sprout. Without actually knowing where they were sown, we can find them by seeing where the gardener takes his watering can" (p.69). Thus, tracking blood flow is an indirect way of observing neurons at work.

In addition, fMRI is fast. A set of images covering the whole brain is typically acquired every 2 to 3 seconds with a spatial resolution of a few millimeters. According to Amaro Jr. and Barker (2006, p.222), "the signal intensity of each pixel within the image is compared to a model of the expected BOLD response to the paradigm, and any signal changes detected are statistically tested for significance", allowing the researcher to correlate increases in the signal with behavior. Statistical processing as well as signal averaging is indispensable due to the difficulty in detecting changes in the signal. For instance, in a scanner of 3 T, the BOLD effect normally gives a 2 to 10% signal change against a background of physiological noise (caused by heartbeat, breath and eye blink). Signal changes are mapped into three-dimensional locations in the brain: voxels. A voxel can contain hundreds of thousands, or millions of neurons. As fMRI data are four-dimensional, in space and time, "each voxel has an associated one-dimensional time series of observed signal intensities" (Pavlicová, Cressie & Santner, 2006, p.277).

It is important to highlight that the term *activation* implies "only relative changes in MRI signal intensity" (Bookheimer, 2002, p.154).

Using fMRI to investigate higher-level cognitive processes as language depends "on the systematic mapping between a task presented to a participant and the brain structure that is activated" (Buchweitz, 2006, p.6). One of the most widely used methods, cognitive subtraction[5], entails comparing brain activation in different situations. For example, when a participant is reading sentences in her mother tongue language and in her second acquired language, it is possible to compare the differences in brain activation between the two conditions. Such cortical areas of the brain will be reported in this work with their anatomical names and the Brodmann areas numbers (BA). A BA is a region of the cerebral cortex defined by its cytoarchitecture, or histological structure and organization of cells (Huettel et al., 2009; White, n.d.). Figure 1.1 presents a map of BAs. The areas colored with yellow reflect areas involved in thinking, planning, social conduct, decision making, motor execution, and language functions. Areas in green are associated with somatosensory perception, phonological processing and visuospatial imagery. Areas in pink are traditionally implicated in language function, auditory processing, memory, semantic memory retrieval, and emotion. Finally, areas in blue are related to visual perception and processing. Colors in the figure relate to the division of the human brain into four lobes: frontal, parietal, temporal, and occipital, respectively yellow, green, pink and blue in the figure.

[5]Raichle (2006) explains that the Dutch physiologist Donders in the end of the 1800's suggested a general method of measuring thought processes. He had in mind a simple logic: subtracting the time needed to respond to a light from the time needed to respond to a particular color of light. By applying the logic, he discovered that discriminating color required about 50 milliseconds. Raichle believes that Donders was the first to measure a mental process by subtracting a control state from a task state. The first neuroimaging study to apply this logic was conducted by Petersen, Fox, Posner, Minton and Raichle (1988) in their PET study of single-word processing.

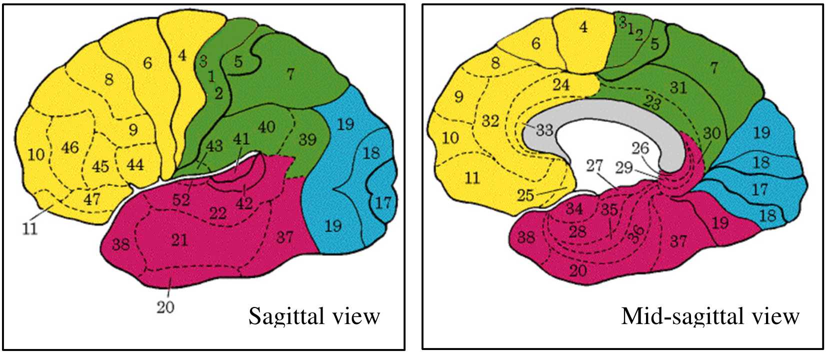

Figure 1.1. Brodmann's areas
(available at <http://www.umich.edu/~cogneuro/jpg/Brodmann.html>)

In the results and discussion chapters, brain areas are identified according to the Montreal Neurological Institute (MNI) coordinates[6] and anatomical automatic labeling (AAL) (Tzourio-Mazoyer et al., 2002) as operationalized in the Statistical Parametric Mapping (SPM8) software (Wellcome Trust Centre for Neuroimaging, University College London).

Brain images, be them structural or functional, are presented in different cuts. Generally, researchers publish sagittal slices, but they also use coronal and axial slices in their papers. Sagittal sections separate left from right, thus, providing readers with a lateral view or a medial view. Coronal sections separate the front from the back, while axial or horizontal sections separate the top from the bottom. A dorsal view shows the brain looking from above and a ventral view shows the brain looking from below. Figure 1.2 in the next page shows how one can get oriented in the human brain. As the brain cortex (outer layer) is a folded-up sheet of cells, it forms gyri and sulci. Gyri (singular: gyrus) mean

[6]Similar to a GPS, the MNI coordinate system is a "geometrical positioning system [...] that consists of three perpendicular axes normalized for brain size" (Dehaene, 2009, p.70). In the MNI coordinate system, "the measurements are -42 mm along the lateral axis, -57 mm along the posterior direction, and -12 mm along the vertical axis" (Dehaene, 2009, p.334). The coordinates are derived "from an average of MRI structural images from several hundred individuals" (Huettel et al., 2009, p.524). Such a system allows investigators to compare locations of brain activity across centers, imaging modalities, and participants. Locations are reported in *x*, *y* and *z* coordinates, in brackets.

hills, thus, they are the ridges in the surface of the cortex. Sulci (singular: sulcus) refer to the valleys in the cortex.

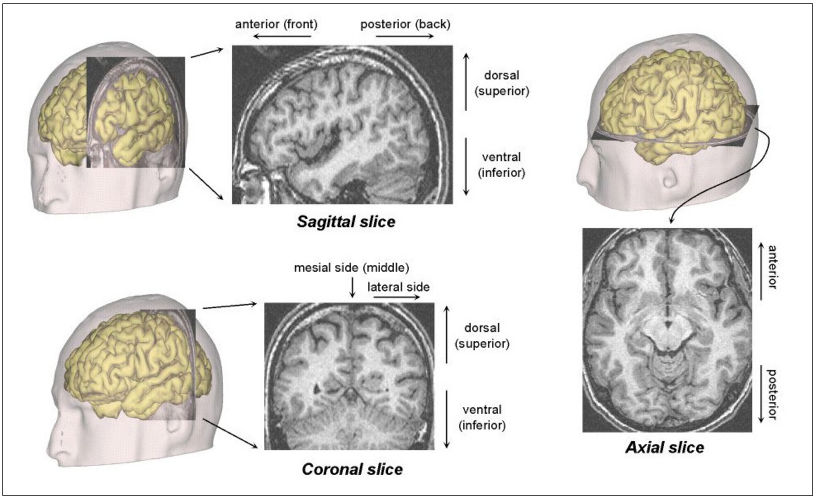

Figure 1.2. Part of the figure "Getting oriented in the brain" presented in Dehaene (2009, p.xii)

Given that the reader was presented with some essential information and nomenclature about the human brain and the fMRI technique, I believe that the reader will be able to follow the description of the literature, the method, the results, the discussion and the conclusion of this investigation. Let us now turn to the significance of the present study.

1.4 SIGNIFICANCE OF THE WORK

The present study adds to existing research on bilingual and monolingual sentence comprehension in four major ways. First, because it investigates the processing of L1 and L2 in Portuguese-English late bilinguals, a scarcely researched population in neuroimaging studies. Secondly, it directly explores language processing in the brains of bilinguals compared to monolinguals. Third, it attempts to identify the semantic neural representation of sentences in Portuguese based on the brain activation for the same sentences in English, and vice versa, in late bilinguals. As well, it applies a model based on independent monolingual English data to decode sentences in Portuguese in bilinguals and monolinguals. Fourth, it investigates the effects of proficiency, working memory capacity, word length and lexical frequency in the activation of bilinguals and monolinguals.

Though this dissertation does not aim at establishing pedagogical implications, I believe that a better understanding of the bilingual brain may afford some contribution to the understanding of the mechanisms underlying the exceptional ability to process written input in two different languages. By comparing the brains of bilinguals and monolinguals processing their L1, it may have some impact on the understanding of how reading comprehension processes differ in the brains of monolinguals compared to the brains of bilinguals.

This study might contribute to the field of Psycholinguistics and Cognitive Psychology by adding neuroimaging data about the processing of words in the context of sentences in bilinguals and monolinguals. Readers' cognitive response might inform models of language comprehension and our understanding of how linguistic information is processed at different levels of cognition. As well, it might help advance the understanding of mental processes involved in reading comprehension. All in all, its significance lies in its modern and interdisciplinary contribution to cognitive studies of bilingual and monolingual language comprehension.

1.5 ORGANIZATION OF THE DISSERTATION

In order to report on the study conducted to explore the processing of L1 and L2 in the brains of monolinguals and bilinguals, the present dissertation is organized into six chapters, including the present introductory chapter (1).

Chapter 2 addresses the review of the literature on reading comprehension, the organization of concepts in the brain and bilingualism. Initially, attention is devoted to the processes involved in the comprehension of words and sentences, to the models of reading comprehension as well as to the effects of individual differences in reading comprehension. Then, the organization of concepts in the brain is presented, with focus on definitions, models and the neural bases of concepts and representations. Finally, the topic bilingualism is examined in four subsections. Models of bilingual word representation are presented along with empirical evidence from word-level and sentence-level neuroimaging studies and from a comparison between the brains of monolinguals and bilinguals processing their L1.

Chapter 3 outlines the objectives, research questions and hypotheses that guide this investigation. In addition, it describes the research design adopted for the present study, including a description of participants, the experimental paradigm, the fMRI procedure, data processing and analysis.

Chapter 4 reports the results of the analysis conducted with the data. It is subdivided into three subsections. The first reports the findings from the sentence-level analysis; the second, the results from the word-level analysis; and the third, the sentence neural representation identification results.

Chapter 5 discusses the findings reported in the results chapter in the light of the literature reviewed in chapter 2. The text is divided into subsections according to the research questions posed in the method chapter. The first approaches the representation of L1 and L2 in the bilingual brain; the second, the representation of L1 in the bilingual and in the monolingual brain; the third, the semantic neural representation identification; the fourth, L2 proficiency and working memory capacity effects; and the fifth, word length and lexical frequency effects on brain activation.

Chapter 6 presents and comments on a summary of the main findings of this study by reiterating the research questions, hypotheses and findings. In addition, it reports the limitations of the study, and mentions suggestions for further research. In the sequence, the reader finds the references and appendices of the study.

CHAPTER 2
REVIEW OF THE LITERATURE

A review is limited to the reviewer's own understanding of the topic and how the conclusions of each paper fit together. (Price, 2010, p.62)

This chapter aims at presenting some theoretical background and empirical data about the reading processing in L1 and L2. It is organized in three main sections. The first part, with four subdivisions, addresses the reading process for word and sentence comprehension, working memory as a source of individual differences, as well as how these processes take place in the brain. The second section, subdivided into three parts, discusses how the mental lexicon is organized, presents models, as well as empirical evidence provided by neuroimaging studies. And the third section, subdivided into four parts, aims at offering a concise review on bilingualism: models of word representations, results from neuroimaging studies on the word- and sentence-level processing, as well as a comparison of monolinguals and bilinguals in respect of the brain areas activated when processing their native language. The review of the literature presented here is not meant to be exhaustive. Instead, I tried to cover the aspects that were considered fundamental in each area discussed and which were used to frame the present investigation.

2.1 READING: FOCUS ON DECODING WRITTEN WORDS AND SENTENCES

As stated in the introduction, language comprehension depends on understanding the meaning of individual words, so that we are able to understand the relationship between words in a sentence, in a paragraph, discourse as whole. At this very instant, while your eyes scan these pages, your brain, with its uncountable connections, accomplishes an amazing feat: to read. With quick movements, your eyes recognize written input. Your brain receives the information captured by your eyes and starts a parallel astonishing orchestration of processes that aims at building a meaningful mental representation of what you are reading. Although readers may not be conscious of all the processes involved in written input recognition and comprehension, it happens, all the time, in the society we live in. In this section, I will present, very briefly, Dehaene's (2009) view on reading followed by Kintsch and van Dijk (1978) and Gagné, Yekovich and Yekovich (1993) models of reading as well as empirical behavioral and neuroimaging studies. The objective is to describe what happens in the reader's mind as s/he understands words, sentences, paragraphs, and constructs meaningful representations of texts and also with the purpose of locating the reader with respect to the components this study will deal with. I also discuss in this section word-level and sentence-level processes as well as the role individual differences as working memory capacity plays in reading comprehension.

2.1.1 Word-level processes

According to Dehaene (2009), reading is a complex ability that ought to be learned for us to live in society. He believes that the reader's brain displays a set of mechanisms that were adapted, through evolution, to reading. For several centuries, such a gift remained a mystery. With the advent of technology, "the brain's black box" was open to investigation (Dehaene, 2009, p.1). Advances in many fields, such as Psychology, Linguistics and Neuroscience, have instigated researchers to disentangle the *mysteries* involved in our ability to read. A variety of studies have been providing insights for the area: behavioral, eye-tracking, neuroimaging (mainly PET and fMRI), and neurophysiological (ERPs) studies. Dehaene made use of brain imaging methods to understand how the brain *deciphers* written words. He explains that our brains were not designed for reading; we were taught how to read. Our brain circuitry was *recycled*, adapted to read. For Dehaene and his recycling hypothesis, there is an area in the occipito-temporal region called the visual word form area (VFWA)[7], whose neurons are originally devoted to the activity of responding to visual stimuli. Such neurons engage in the new task of recognizing letters and words. Glezer and colleagues (2015) empirically tested this hypothesis by training

[7]According to Dehaene (2009), the VWFA is located in the fusiform gyrus, between the inferior temporal gyrus and the parahippocampal gyrus. The MNI coordinates are [-44, -58, -15]. For Bolger, Perfetti and Schneider (2005), they are [-42, -57, 15]. For Glezer and colleagues (2015), the coordinates should be [-46 +/- 7, -57 +/-7, -15 +/-6]. Recent research conducted by Vogel, Petersen and Schlaggar (2014) suggests the VWFA as a general use region for tasks that require processing properties, thus, "making it particularly useful for reading" (p.8).

participants implicitly on novel words and concluded that the neurons in the VWFA are selective for whole words, thus, allowing for the fast recognition of familiar words. Thereby, the capacity to read is the result of a sophisticated evolutionary process granted by the plasticity of the human brain and the human instinct to learn and teach.

Just and Carpenter (1980) conducted an eye-tracking study to investigate how reading takes place from eye fixations to comprehension. They assumed that it is possible to learn about the processes involved in comprehension by examining where the readers pause, fixate their eyes. They explain that an average fluent reader is able to read about 200 words per minute in scientific texts. In addition, readers fixate every word and there is a large variation in the duration of individual fixations as well as the total gaze duration on distinct words. The researchers theorize that gaze durations reflect the time necessary to perform comprehension processes. When readers are accessing infrequent words, integrating information and making inferences, longer pauses occur because of greater processing loads. Dehaene (2009) complements this view by explaining that the majority of content words such as nouns and verbs ought to be fixated at least once, while function words and grammatical markers as *the, it, is* may sometimes be skipped.

Recognition of words presented in the visual modality is based on a match between printed strings of letters and lexical representations. When we encounter a word, it is hardly possible to avoid understanding its meaning (Pulvermüller, 2012). Two parallel processing routes can be used to lead to meaning: (1) the phonological route, and (2) the lexical route. The first converts letters into speech sounds, while the second, gives direct access to a mental dictionary of word meanings (Dehaene, 2009; Frost, Katz & Bentin, 1987). Jobard, Vigneau, Simon and Tzourio-Mazoyer (2011) name the routes as grapho-phonological route and lexico-semantic route. In spite of receiving different names, their meanings are comparable. The first route (phonological/grapho-phonological) entails linking orthographic units to their phonological equivalents; consequently, access to words happens via their pronunciation. The second route (lexical/lexico-semantic) pairs orthographic forms of entire words and the semantic representations they stand for. In alphabetic languages as English, beginners in the art of reading use the phonological route as default until their familiarity with the orthography allows them to associate word forms to meanings. Petersen and colleagues (1988), in the first PET study of single-word processing in the brain with skilled readers, already signaled that words may be processed directly from visual systems without undergoing phonological recoding.

According to Dehaene (2009), "all writing systems oscillate between an accurate representation of sound and the fast transmission of meaning" (p.38). Both routes (phonological and lexical) are automatically activated during word recognition and act in parallel to mediate lexical access. Dehaene (2009) explains that when we encounter very irregular, rare or novel words, readers preferentially access them using the phonological route: decode the letters, convert them into pronunciation and finally access the meaning of the sound pattern. On the other hand, when readers are confronted with frequent words or those who have an exceptional pronunciation, they use a direct route that accesses the words' meaning and then uses the lexical information to recover its pronunciation. Generally, individuals have a reason to wanting to pronounce the word after having its meaning at hand, as interest, need, or time.

Among alphabetic writing systems, there are key differences in the way they mirror the phonemic structure of their spoken languages. Frost, Katz and Bentin (1987) and Katz and Frost (1992) proposed the *orthographic depth hypothesis* that puts languages into a continuum from shallow to deep orthography. In shallow orthographies, the phonemic and orthographic codes match, phonemes are represented by graphemes in a direct fashion, thus, "orthography tracks phonology" (Katz & Frost, 1992, p.149). Deep orthographies present a more opaque relation of spelling to sound; the same letter or grouping of letters may represent different phonemes in different contexts, therefore, different letters may represent the same phoneme. As aforementioned, languages vary along the continuum. For instance, on one end, Italian has a transparent spelling system; with 30 phonemes, "every letter maps onto a single phoneme" (Dehaene, 2009, p.31), facilitating the correct pronunciation of words. On the other end, English exhibits an opaque spelling system; depending on the speaker and on the counting method, the language has from 40 to 45 phonemes, complicating mapping of letters to sounds. Essential for this study, Portuguese is less transparent than Italian and Spanish and less opaque than French and English. According to Scliar-Cabral (1974), the Portuguese language has 33 phonemes.

Palesu and colleagues (2000) conducted behavioral and PET studies with Italian and English university students. They concluded that "reading in a complex and inconsistent orthography comes at a considerable cost" (p.93). Italians read faster and more efficiently because of the consistent mapping between individual letter sounds and sounds of such letters in the context of words. English readers relied more on semantic/orthographic processes, which seemed to be automatically evoked, given the degree of orthographic complexity.

As regards the brain implementation of word recognition processes, the two routes that allow access to meaning and sounds seem to involve distinct sets of brain areas in the left hemisphere. As figure 2.1 in the next page (Dehaene, 2009, p.106) shows, occipito-temporal regions support visual analysis; superior and middle temporal gyri, supramarginal gyrus[8] and the *pars opercularis* of the inferior frontal gyrus are involved in phonological processing; and middle temporal gyrus, basal temporal region[9], and the *pars triangularis* of the inferior frontal gyrus subsidize semantic access.

[8]The supramarginal gyrus, as explained by Stoeckel and colleagues (2009), is part of the inferior parietal lobule and is connected to regions involved in phonological processing, as the "auditory association regions of posterior superior supratemporal plane" and a region of the IFG (p.1092). Their TMS (transcranial magnetic stimulation) findings suggest that the supramarginal region (BA40) automatically computes "the sound of a word even when the task does not explicitly require it" (p.1091).

[9]The basal temporal region is traditionally referred to as Basal Temporal Language Area. According to Abou-Khalil, Wertz, Abou-Khalil, Welch and Blumenkopf (1996), "it is located in the fusiform gyrus in the basal temporal lobe; however, it may extend into the inferior temporal gyrus and the parahippocampal gyrus" (p.173).

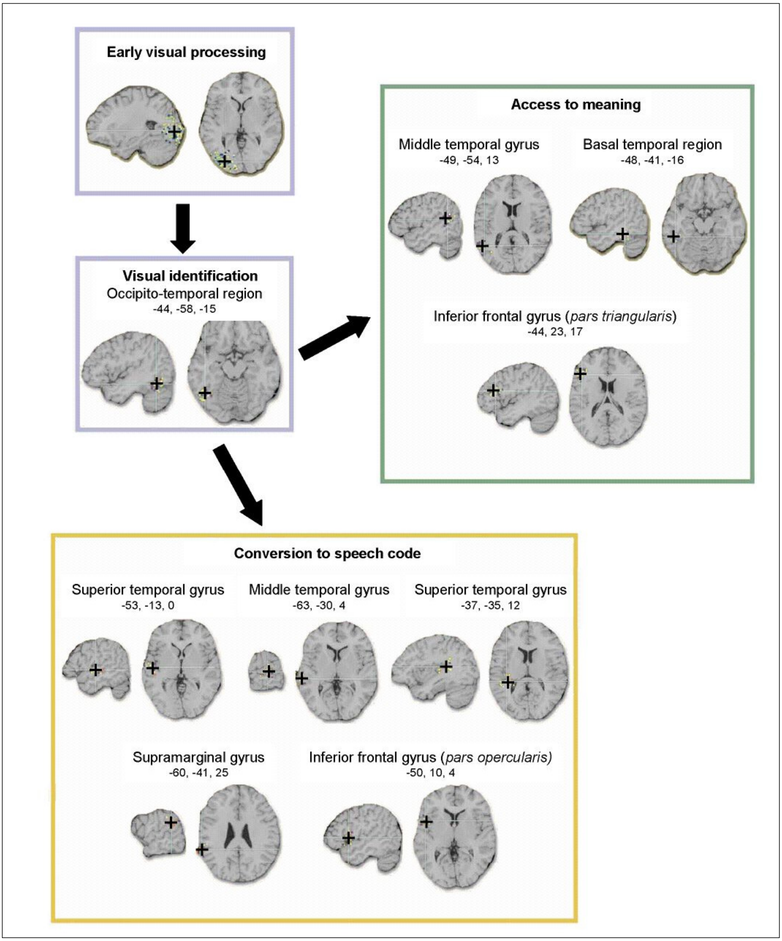

Figure 2.1. The two reading routes in the brain (Dehaene, 2009, p.106)

Palesu and colleagues (2000) found stronger activation in Italian readers in the left planum temporale at the temporo-parietal junction, a brain region typically associated with phonological processing. English readers showed greater activation in the left posterior inferior temporal region and in the anterior part of the left inferior frontal gyrus.

Dehaene (2009), in his book, proposes an alternative to the classical sequential model of reading in the brain. In his perspective, figure 2.2 reveals that left occipital areas, in particular the VWFA, receive the visual input, identifying the visual form of letter strings. Then, this visual information is distributed to numerous regions all over the left hemisphere that encode meaning, sound pattern and articulation. Although the detailed organization of the networks is not yet fully known, it seems that reading implicates visual and language areas in a bidirectional and simultaneous way. Dehaene recognizes that the cortical connectivity in reading may be much richer than the one depicted in his diagram.

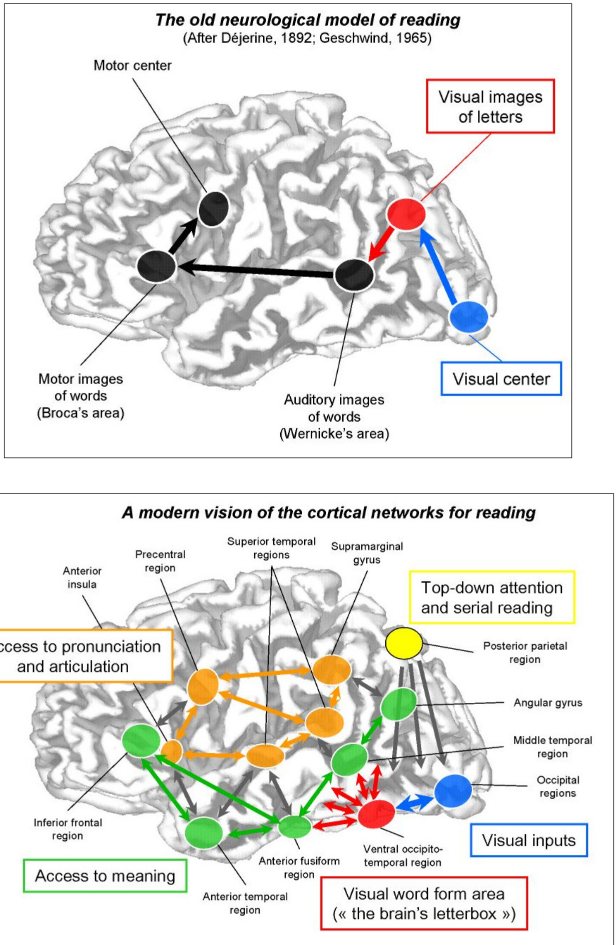

Figure 2.2. The classical neurological model of reading and a modern perspective on how reading takes place in the brain (Dehaene, 2009, p.63). Areas in green and orange are not specific to reading; they are primarily involved in speech processing.

Corroborating this view, Price (1998) reviewed studies on word comprehension and production and found that accessing the semantic system involves more anterior inferior temporal regions and the posterior inferior parietal cortex on the left hemisphere. In addition, the left supramarginal gyrus (BA 40) is involved in translating orthography to phonology. Gitelman, Nobre, Sonty, Parrish and Mesulam (2005) designed a study to explore the neuronal response to three fundamental processes for language: orthography, phonology and semantics. Their results reveal a common network of brain regions that supports word processing: ventrolateral frontal, supplementary motor, posterior mid-temporal, occipito-temporal and inferior parietal areas. In their review, Shaywitz and Shaywitz (2005) indicate three systems that are important for word-level reading: (1) the angular gyrus[10] (temporo-parietal region), that is associated with phonological processes and the conversion grapheme-phoneme; (2) the VWFA, that responds rapidly to words at about 150 milliseconds after the word is presented; and (3) the left inferior frontal gyrus, that is traditionally implicated in articulation and plays a role in silent reading.

Bolger, Perfetti and Schneider (2005), in their meta-analysis of word reading studies, found a striking commonality of localization across tasks and across writing systems in the VWFA. They analyzed studies with alphabetic (English, French, and so on), syllabic (Chinese and Japanese *kana*), and morpho-syllabic (Japanese *kanji*) writing systems. They divided word reading into three component processes: orthographic, phonological and semantic processes. The first process involves bilateral occipital regions, particularly the left fusiform gyrus (where the VWFA is) and the left inferior temporal gyrus (BAs 18, 37, 19 & 37). The second process involves left-lateralized regions: the superior temporal sulcus, the inferior parietal lobe, the inferior frontal, insula and premotor regions (BAs 22, 40, 39, 45, 6 & 9). And the third process involves left-lateralized areas: the anterior fusiform, the inferior and middle temporal gyrus, and the inferior frontal gyrus (BAs 37, 21 &

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[10]The angular gyrus (BA39) "sits at the posterior end of the inferior longitudinal fasciculus which links it with temporal lobe regions implicated in semantic memory" (Stoeckel et al., 2009, p.1092). Seghier (2013) in his review highlighted "the integrative role of the AG in comprehension and reasoning" (p.56). Angular gyrus activation was found for the manipulation of conceptual knowledge, semantic processing, word reading and comprehension, memory retrieval, attention, spatial and social cognition.

44). Despite the variation in visual characteristics and in how these languages map orthography to phonology and semantics, the authors conclude that different writing systems utilize a common network of regions; they engage predominantly the same cortical regions but localization within those regions indicates that there are differences across writing systems.

A recent study carried out by Zaccarella and Friederici (2015) investigated, with fMRI, word processing in the insular cortex, “an entirely hidden portion of cerebral cortex, located in the depth of the sulcus lateralis, below the Sylvian fissure” (p.1). Such region is normally associated with autonomous functions as heartbeat and breathing as well as cognitive functions like awareness. Some studies have reported activations in the insula during language tasks, as in speech and auditory processing at the word and phrasal level. The researchers presented 22 German participants with written words (and pseudowords) and phrases. They used a multi-modal parcellation tool to perform more precise localizations of brain activity. As findings, words elicited significant bilateral insular activation, with clusters peaking at [-33, 23, -2] (55 voxels in the left hemisphere) and at [33, 23, -2] (27 voxels in the right hemisphere).

Some studies have investigated the effect of word length on reading. Scholars believe that brain response is susceptible to how many letters are presented at a time, how fast words are presented, and for how long they remain in the visual field. Mechelli, Humphreys, Mayall, Olson and Price (2000), for instance, in their PET study with six participants examined how word length and visual contrast affect reading. They used words with three, six and nine letters and varied from low to high contrast the way they presented the words. Participants were asked to articulate the words silently while being scanned. Findings revealed that, compared to short words, long words elicit greater activation in the bilateral medial lingual and fusiform gyri, in the right superior lingual gyrus, the medial cuneus and the left motor region. Short words when compared to long ones did not elicit significant activation. The researchers consider the motor area involvement an effect of silent subarticulation. As regards contrast, the lingual gyrus was more activated by low-contrast words and the fusiform gyrus by high-contrast words. Such results suggest that demands on local feature processing and on global shape processing increase with increasing word length. As well, Wehbe and colleagues (2014), in their study about the brain regions involved in reading a chapter of a Harry Potter’s book, found word length effects in the occipital cortex, spreading to the left fusiform areas (VWFA).

Having all this information in mind, let us review some studies about how sentence comprehension is implemented in the brain. It is important to highlight that the studies reviewed in this subsection were all conducted in the participants' mother tongue, L1.

2.1.2 Sentence-level processes

Sentence comprehension not only requires the processing and comprehension of individual words, but it does require combining information from a sequence of words and phrases. At the cognitive level, it involves computing syntactic and thematic relations, using world knowledge to construct a representation of the sentence meaning. Additionally, such processes require mental resources to perform comprehension as well as to maintain active during processing the representations of word meanings and propositions. Propositions are the result of processing, and can be defined as coherent structured units at the sentence level, or basic units of meaning. According to Tomitch (2003), propositions are complete ideas. To Gagné and colleagues (1993), propositions "express or 'propose' relationships among concepts" (p.61). Paradis (2004) argues that when words are presented out of context, "they lose most of their language-specific properties" (p.176). Corroborating this perspective, Perfetti and Bolger (2004) claim that reading sentences engages processes of meaning, reference, syntax and text integration, as well as it requires the support of working memory that are not involved as much in word identification.

Just and colleagues (1996) were the first to study sentence comprehension with fMRI[11]. They asked 15 college-age right-handed students to read sentences and answer comprehension questions while in the scanner. Their results revealed that a network of four areas was recruited to process sentences: the classical left-hemisphere language areas (BA 44 & 45 Broca's area: inferior frontal gyrus, and BA 22 Wernicke's area: superior temporal gyrus) and their right-hemisphere

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[11]Mazoyer and colleagues (1993) were the first to publish a neuroimaging study (PET) about the neural basis of speech (not only individual words). They concluded that speech processing recruits a network of areas, each of which may be specialized in one aspect but requires support from the others to achieve comprehension. They suggested Broca's area as crucial for lexical and conceptual processing. As the focus of this section is on reading, we chose not to review this study.

homologues. Although the left hemisphere was more strongly activated, right hemisphere areas were recruited when sentences were structurally more complex (subject- and object-relative clauses). The authors infer that the brain recruits more neural tissue of a network when comprehension demands are higher. As well, they conclude that not just an area but several contribute to sentence comprehension.

Hashimoto and Sakai (2002) investigated whether there are specialized neural systems for sentence comprehension. Sixteen native speakers of Japanese were fMRI tested in a series of syntactic decisions and short-term memory tasks. In the literature, the left inferior frontal gyrus is traditionally implicated in comprehension processes. It is believed that the anterior part (BAs 45 & 47) participates in semantic processing and the posterior part (BAs 44 & 45) contributes to phonological and lexical processing, although other studies have implicated the posterior part in syntactic processing. As results, the authors found evidence of specialized left prefrontal areas in sentence comprehension: the left dorsal prefrontal cortex for short-term memory and left inferior frontal gyrus for analyzing syntactic structures. Gabrieli, Poldrack and Desmond (1998) concluded, in their review paper, that the left prefrontal cortex plays a crucial role in language and memory, such as in semantic analyses and implicit memory. They explained that left prefrontal activations "seem to reflect processes that are important for enhancing memory for materials encountered in particular episodes" (p.907). As well, it can reflect semantic selection processes, as "left-frontal and right-cerebellar activations increased or decreased in tandem across conditions" (p.908).

As syntactic and semantic information are so intimately intertwined, Newman, Just, Keller, Roth and Carpenter (2003) explored the contribution of two subregions of Broca's area: *pars opercularis* (BA 44) and *pars triangularis* (BA 45) in the processing of sentences followed by a grammaticality judgment task. Thirteen participants were fMRI scanned while they read conjoined-active and object-relative sentences with two types of ungrammaticalities: noun-verb agreement and extra verb addition. As expected, the object-relative clauses elicited more brain activation due to complexity. The data suggest that the *pars triangularis* is differentially involved in semantic and thematic aspects of comprehension; and that the *pars opercularis* is more involved in building and manipulating the syntactic structure of sentences. In addition, the researchers found activation in the left intraparietal sulcus, generally implicated in visuo-spatial processing. They interpreted such activation as involved in the generation of visual images of the actions depicted in the sentences.

A more recent study conducted by Frankland and Greene (2015) examined with fMRI how the brain encodes "who did what to whom" (p.1) in visually presented sentences, such as *The truck hit the ball* and *The ball hit the truck*. They found that agents (*who did it?*) are processed by the upper bank of the left superior temporal sulcus [-46, -18, 1], and patients (*to whom was it done?*), by the lateral bank of the left superior temporal gyrus [-57, -10, 2]. They also found activation in the left amygdala [-28, -7, -18], which they interpreted as affective processing. Their results support the possibility "that the explicit representation of abstract semantic variables in distinct neural circuits plays a critical role in enabling human brains to compose complex ideas out of simpler ones" (p.6).

Hitherto the left hemisphere seems to be the responsible for language comprehension at the word- and sentence-level, since the studies reported in this review do not suggest specific roles for areas in the right hemisphere (only Just and colleagues reported activation in right-hemisphere areas when task demands were high). Nevertheless, Purves and colleagues (2008) explain that the true significance of lateralization for language "lies in the efficient subdivision of complex functions between the hemispheres rather than in any superiority of one hemisphere over the other" (p.688-689).

In this line, Jung-Beeman (2005) hypothesizes that when natural language comprehension is at stake, the right hemisphere plays an important role. He reviewed brain lesion, neuroimaging, and neuroanatomical studies and suggested "at least three distinct but highly interactive components of semantic processing" (p.513). The three components recruit bilateral areas. The first, *semantic activation* requires the participation of the superior middle temporal gyri (Wernicke's area). *Semantic integration*, the second, "supports message-level interpretation by computing the degree of semantic overlap among multiple semantic fields" (p.515) and recruits the anterior superior temporal gyri as well as the temporal poles. The last component, *semantic selection*, selects the relevant concept among the ones previously activated and implicates the inferior frontal gyri. Jung-Beeman theorizes that such processes occur bilaterally but with some differences. The left hemisphere would process "the dominant, literal of contextually relevant meaning while inhibiting features related to the subordinate or contextually irrelevant meanings" (p.514); it presents, thus, a fine semantic coding that quickly selects a small number of relevant meanings. The right hemisphere would maintain a more diffuse, semantic activation, with distant and unusual semantic features, secondary meanings; thus, it presents a coarse semantic coding in which a broad spectrum of meanings is weakly activated. For Jung-Beeman, these differences enable researchers to investigate language taking into consideration the prompt and tight connections in the left hemisphere, and the maintenance of broader meaning activation in the right hemisphere.

Jung-Beeman's coarse coding hypothesis was investigated in an fMRI study Mason and Just (2007) conducted to understand how lexical ambiguities in sentence comprehension are solved. Their stimuli were sentences with two types of ambiguities: (1) biased ambiguous word, when one meaning is dominant and the other, subordinate, for instance, the word *ball* in *This time the ball was moved because it was always so well attended*; (2) balanced ambiguous word, when a word has two equally possible meanings, as the word *pitcher* in *Of course the pitcher was often forgotten because it was kept on the back of a high shelf*. They also included matched control sentences. As results, they found bilateral extra activation in the inferior frontal gyrus as well as the caudate in the basal ganglia[12] for ambiguous words. They also found bilateral middle and superior frontal activation for sentences with biased ambiguous words, which they believe to be an indicator of a coherence monitoring process. The researchers consider the caudate to be involved in selection, and the inferior frontal gyri activation to reflect semantic reanalysis. Mason and Just concluded that "lexical ambiguity evokes extra processing that could be attributable to generation, maintenance, and selection of multiple meanings" (2007, p.118).

More recently, Buchweitz and collaborators (2009a) compared brain activation patterns associated with reading and listening comprehension of sentences in Portuguese. As results, they found that reading comprehension recruited more left-lateralized regions, especially the inferior frontal cortex and the fusiform gyrus, while listening comprehension evoked bilateral brain activation. They

[12]The basal ganglia "consist of several interconnected subcortical nuclei with major projections to the cerebral cortex, thalamus, and certain brain stem nuclei" (Kandel et al., 2000, p.854). Components of the basal ganglia: dorsal striatum (caudate nucleus and putamen), ventral striatum (nucleus accumbens and olfactory tubercle), globus pallidus, ventral pallidum, substantia nigra and subthalamic nucleus. Relevant for language processing, Bohsali and colleagues (2015) found structural connectivity between Broca's area and the thalamus, suggesting that they are involved in linguistic functions similar to those subserved by BAs 44 and 45.

concluded that the VWFA probably plays a larger role in deeper orthographies (like English) than in Portuguese. This study will be revisited in the section about sentence-level studies on bilingualism.

Prat and Just (2011) also investigated individual differences in sentence comprehension with 27 undergraduate students. Such participants were presented with sentences in various degrees of complexity. From their study, three concepts are crucial for this study: neural adaptability, neural synchronization, and neural efficiency. The first, neural adaptability, refers to a cortical network that is engaged in performing a task being able to adapt to changing information processing demands. Neural synchronization relates to "the extent to which the activation levels of 2 regions rise and fall in tandem" (Prat & Just, 2011, p.1749). Neural efficiency refers to the amount of mental resources required to perform a task. Prat, Mason and Just (2011) explain that neural efficiency relates to "doing more with less" (p.1). Besides these three concepts, the dynamic spillover hypothesis is also crucial for this study. It refers to the idea that "lateralized processes "spill over" into contralateral hemispheres with increased difficulty" (Prat, Mason & Just, 2011, p.3). That is exactly what Just and colleagues (1996) found in their study when syntactic complexity increased.

Xu, Kemeny, Park, Frattali and Braun (2005) were the first to examine, with fMRI, the neural systems involved in processing language at three levels: words in isolation, in a syntactic structure (individual sentences) and in a narrative (fables) in a single experiment. As results, reading activated, at all levels, the core left hemisphere (LH) language areas. At the sentence level, the researchers observed more widespread activation in such areas, particularly in regions within the frontal operculum. At the narrative level, they observed additional demands reflected in robust activations in the medial prefrontal cortex and precuneus. As the levels increased, they found growing right hemisphere (RH) contribution. As hypothesized, they found that both hemispheres were active in the story comprehension, but the right hemisphere activation increased at the end of the narrative segment, as the details were synthesized and woven into a coherent whole. Such differences related "to the distinctive combinatorial and semantic features of lexical, sentential, and discourse conditions" (p.1014).

Mason and Just (2006) propose speculative neural networks for discourse comprehension based on neuroimaging findings. In their proposal, the first step in discourse processing is the recruitment of a basic left-hemisphere sentence network. Such basic processes include visual, phonological, lexical-semantic, and syntactic processing. They highlight that discourse processing "occurs on a word-by-word, moment-to-moment level in parallel with the lower levels of language processing" (p.788). As each word is being processed, an interpretation is being constructed within the context of the sentence(s), of the passage. Their network proceeds with a coarse right-hemisphere semantic processing network; a dorsolateral prefrontal coherence monitor network; a left frontal-temporal text integration network; a medial frontal protagonist/agent interpreter network; and an intraparietal sulcus spatial network. As the present study deals with single sentence processing, these networks will not be reviewed here.

2.1.3 Models of reading: the whole process, from words to discourse

In this subsection, I chose to review a few reading models that are related to the present study, such as Kintsch and van Dijk's *textbase model* (1978), van Dijk and Kintsch's *situational model* (1983), and Gagné et al.'s *componential model* (1993). Initially, it is necessary to establish exactly the meaning of the term model. Davies (1995) defines it as a formal theory, with guesses and predictions about a hidden process, which may be tested through experimental research. In the case of reading, most models represent visually "what goes on in the eyes and the mind when readers are comprehending (or miscomprehending) text" (Davies, 1995, p.57).

Kintsch and van Dijk's textbase model (1978) is concerned with semantic structures, which are the result of processing. These semantic structures are characterized at two levels, the level of microstructure and of macrostructure. The microstructure involves the local level of discourse and the structure of the individual propositions and their relations, which authors from text linguistics call cohesion (Koch, 1993). In this line of thought, the textbase is understood as the hierarchically organized set of propositions from the text surface, including the connections between them. The macrostructure refers to the global level of discourse, the discourse as a meaningful whole, and portrays relationships which text linguists call coherence (Koch & Travaglia, 1989). Both levels relate to semantic mapping rules, the macrorules, on the grounds that the discourse is expected to be coherent and propositions should be connected and globally organized at the macrostructure level so that a meaningful mental representation of the text is built. The first macrorule proposed by Kintsch and van Dijk (1978) involves the *deletion* of detailed and redundant information. The second requires *generalization* using superordinate terms or categorizations, since a sequence of propositions may be replaced by a more general proposition. Finally, the third macrorule involves the *construction* of a topic sentence when that is not provided in the text, as the authors postulate that "each sequence of propositions may be substituted by a proposition denoting a global fact" (Kintsch & van Dijk, 1978, p.366).

van Dijk and Kintsch (1983) later developed the model of semantic representation into the situation model. It is the result of the interaction between the construction of a textbase and the construction of a general understanding of the text based on background knowledge. The construction of a coherent situation model requires the reader to perceive the text as a coherent whole at the same time s/he is building a textbase. The situation model is the result of processing, the cognitive representation of events, actions, persons and the situation that the text is all about. van Dijk (1999) adds that readers construct a mental representation of the properties of the situation that are currently relevant to them. For him, this mental representation is "the *subjective interpretation* of the context" (p.124) that constrains the way readers understand discourse. In this realm, successful readers are the ones able to build a coherent mental representation of the text by constructing a textbase and integrating it with their background knowledge, thus building a situation model of text.

In line with those two models, Gagné et al. (1993) understand reading comprehension as the construction of an adequate mental model of the text, relying on the interplay between declarative and procedural knowledge. Declarative knowledge, also considered conceptual understanding, involves all the knowledge readers possess about letters, phonemes, morphemes, words, ideas, schemas and topics; thus, semantic knowledge. Procedural knowledge, also referred to as skills and strategies, include the four component processes of reading: decoding, literal comprehension, inferential comprehension and comprehension monitoring. In their model, these processes happen in parallel, simultaneously, at least in proficient reading.

The lowest-level processes involve the *decoding* of printed information and *literal comprehension*. *Decoding* refers to cracking the print code to make it meaningful and it is subdivided into *matching* and *recoding*. The former refers to accessing meaning in long-term memory and the latter, to sounding out the word to have access to the stored meaning. This component is the one emphasized in Dehaene's (2009) view of reading presented in a previous subsection of this chapter. It may be possible to relate *matching* to the lexical route and *recoding* to the phonological route. The second component, *literal comprehension*, refers to deriving literal meaning from print and it is subdivided into *lexical access* and *parsing*. The first refers to accessing the best interpretation, in the context of the sentence, of the word from all the options activated in our mental lexicons. Whereas the second involves using the syntactic and linguistic rules of the language for putting words together to form meaningful ideas, or propositions, the "units of declarative knowledge that represent the meaning of the text" (Gagné et al., 1993, p.273) that Kintsch and van Dijk (1978) refer to.

The highest-level processes involve *inferential comprehension* and *comprehension monitoring*. The former allows the reader to go beyond the information literally stated in the text by giving the reader a broader understanding of the ideas from the text. *Inferential comprehension* is subdivided into *integration*, *summarization* and *elaboration*. The first subcomponent is responsible for connecting propositions and it occurs within sentences, across sentences, and across paragraphs. At this level, the reader makes the necessary inferences to understand the text, at the microstructural level (Tomitch, personal communication, 2012). The second subcomponent, *summarization*, aims at producing, in the reader's mind, a macrostructure that expresses the main ideas in the text. The processes of *integration* and *summarization* involve the production of necessary inferences so that the reader is able to extract the essence of the text in order to produce a coherent mental representation of the content of the text (Tomitch, 2012). And the third subcomponent, *elaboration*, allows the reader to use her/his background knowledge to complement the new ideas from the text, referring to what van Dijk and Kintsch (1983) call the situation model. Finally, *comprehension monitoring* is the highest-level process, although this does not mean that it happens last. Proficient readers monitor their reading throughout the reading event. At the start, readers establish an objective, set a goal and select the appropriate strategies to reach such a goal. Then, they check whether the objective is being reached during reading and remediate, in other words, change strategies when reading is not meeting the goal previously set.

In this realm, it is possible to conclude that those models contribute to understanding how sentences are processed. In this study, sentences such as *The family was happy* and *The couple visited the embassy* will be presented to participants in the written mode and they will be asked to think about the meaning of such sentences. When reading and thinking about each word, each phrase, each sentence, participants will activate brain areas related to the subprocesses. Thus, in

Kintsch and van Dijk's terms (1978), this study stands at the level of the microstructure, the textbase. In Gagné et al.'s (1993) model, at the lowest-level processes: *decoding* and *literal comprehension* components, since participants will be accessing meaning in their long-term memory or sounding out the words (*matching* and *recoding*) as soon as they encounter each word on the screen. As well, they will be accessing the best interpretation of such words in the context of sentences (*lexical access*) and will form a meaningful representation of such sentences.

I acknowledge the fact that I am working with low-level component processes, which may be less relevant for some lines of research; nonetheless, it does not diminish the importance of investigating the representation of sentences in the brain. According to Mason and Just (2007), "one of the building blocks of language comprehension is the ability to access the meaning of words as they are encountered and to develop an interpretation that is consistent with the context" (p.115). Furthermore, I would add that by comprehending how sentences are processed in monolinguals and bilinguals, we will be better informed about how discourse comprehension takes place in the brain. As well, we should bear in mind that there are individual differences in reading comprehension, the topic of the following subsection.

2.1.4 Individual differences in reading comprehension

> *Language is a process of free creation; its laws and principles are fixed, but the manner in which the principles of generation are used is free and infinitely varied. Even the interpretation and use of words involves a process of free creation. (Noam Chomsky, 1987, p.152)*

Reading comprehension is viewed in this study as a complex cognitive process and as the interaction between text and reader. It varies from individual to individual due to a wide range of factors such as motivation, aptitude, working memory capacity (WMC), background knowledge, among others. This subsection presents a very brief review[13] about the relevant literature on working memory (WM) for the present

[13]For a more in depth review on the construct and models, the reader is referred to Bailer (2011).

study. Working memory is essential for many cognitive tasks and relies on the ability to maintain stable active representations over short periods of time (Bledowski, Rahm & Rowe, 2009).

Baddeley and colleagues (Baddeley & Hitch, 1974, 1994; Baddeley, 1992, 2001, 2003) proposed a multicomponent model of WM consisting of a control system of limited attentional capacity, termed the central executive, which is assisted by three subsidiary systems: the phonological loop, the visuospatial sketchpad and the episodic buffer. Briefly, the central executive plays an essential role in executive functions as focusing, dividing and switching attention, relating content of WM to long-term memory (LTM). The phonological loop stores and rehearses speech-based information. The visuospatial sketchpad is the workplace for holding and manipulating visual and spatial information. Finally, the episodic buffer is assumed to represent a storage system using a multimodal code.

There is agreement among researchers that WM plays an important role in all kinds of human cognitive activities (Tomitch, 2003), as it is the system responsible for simultaneous storage, maintenance, and processing of information in the short term. It is known as ‘an arena of computation’ where storage and processing compete for capacity in the system (Daneman & Carpenter, 1980; Just & Carpenter, 1992; Tomitch, 2003). It is the place where mental activity happens; its limitation refers to how much work can be done at a time, how much WMC is available to be shared among the simultaneous processes. This limited capacity differs among individuals and such differences are good predictors of performance on cognitive tasks: individuals with larger WMC perform better on these tasks than individuals with smaller capacity. The explanation proposed is that who has greater WMC is able to hold and manipulate in WM more information relevant to completing complex tasks, and as a result showing better performance.

Research on individual differences in WMC has been, more extensively, carried out in the L1 and, less extensively, in the L2. Positive correlations have been found with a wide variety of higher order cognitive tasks, as reading and listening comprehension in general, but also in subprocesses as main idea construction, resolution of ambiguities, inferential comprehension, strategy implementation, and text structure, to mention a few (Bailer, 2011). Compared to monolinguals, bilinguals are better able to direct their attention to task-relevant information and further maintain their attention despite adverse interference (Yang et al., 2005).

To measure WMC, Daneman and Carpenter (1980) devised the Reading Span Test (RST). It involves the comprehension of sentences in addition to the recall of the last words of a group of presented sentences. A person's reading span is the maximum number of final words recalled in the order they were presented. As the RST presents heavy processing requirements, the underlying assumption (Daneman & Carpenter, 1980) is that these requirements may decrease the amount of additional information that can be maintained. The results are "used to predict performance on other cognitive skills such as reading, comprehension and reasoning" (Tomitch, 2003, p.33). Daneman and Carpenter (1980) emphasize that an individual's capacity varies according to the efficiency in relation to the processes correlated with a particular task. Following this line, the RST is considered a good predictor of comprehension because it captures many of the processing requirements of sentence comprehension (Daneman & Merikle, 1996). As Cantor and Engle (1993, p.1102) highlight, "when reading, good readers have fast and efficient reading processes that require less WMC than those of poor readers. Thus, good readers have functionally more capacity in reading-related tasks".

To explain how WMC constrains comprehension, Just and Carpenter (1992) proposed a computational model called the Capacity Constrained Comprehension model. The authors state that "both processing and storage are mediated by activation and that the total amount of activation available in working memory varies among individuals" (p.122). When the resource demands of the task exceed the available supply, processing slows down, partial products are generated and performance is affected. Higher spans display more residual capacity to store the words to be remembered in the span task, for the reason that they are more efficient at retrieving information from LTM and at allocating their resources to meet the demands of the task.

In this context, neuroimaging studies have provided information as regards how WM is implemented in the human brain. A great variety of techniques and tasks have unveiled the prefrontal cortex (PFC), the very frontal area of the brain as where WM takes place (D'Esposito et al., 1995; Alloway & Alloway, 2013). Such area has been repeatedly reported in WM studies. Perani (2005) explains that the left dorsolateral PFC is involved in many language tasks, as word generation, semantic and syntactic monitoring, as well as in generating and monitoring sequences, learning associations between stimuli and in WM. In her words, the PFC "is not homogeneous, encompassing many different cytoarchitectonic areas each exhibiting a unique pattern of connections with other cortical and subcortical areas” (p.211), such as with Broca’s area, the intraparietal sulcus, the hippocampus and the amygdala.

Cabeza and Nyberg (2000) reviewed 275 PET and fMRI studies and revealed that prefrontal, frontal and parietal regions of the brain are associated with WM. They explain that areas are recruited according to the nature of the task and difficulty. Investigations that apply verbal tasks generally report activations in BA 44 (Broca’s area) in the LH. The frontal areas normally implicated in general working memory are BAs 6 (supplementary motor area, SMA), 9 and 46 (dorsolateral PFC). The activation of such areas is interpreted as reflecting a rehearsal process that “refreshes the contents” of WM (Cabeza & Nyberg, 2000, p.19). The parietal regions particularly BAs 7 and 40 are typically related to linguistic operations, as retrieving words from LTM and accessing the phonological store. All in all, it is believed that WM consists of a network of areas dedicated to the accomplishment of higher-order cognitive daily tasks such as reading and speaking.

WM as measured by the RST (Daneman & Carpenter, 1980) is also considered an estimate of reading ability. According to Daneman and Merikle (1996), it correlates well with global verbal tests, as the American SAT (Verbal Scholastic Aptitude Test), and with specific tests that evaluate comprehension of written sentences and paragraphs. To illustrate, Jobard and colleagues’ study (2011) considers the reading span an index of reading ability. They investigated word reading and skill in 33 readers of French with fMRI. They required participants to perform the RST, and inside the scanner, read words to their minds (covert reading), since the mouth movement of overt speech would produce noise in the data and would activate language areas related to speaking. They used very frequent words as stimuli since they “are thought to benefit from a direct link between stored orthographical representations and semantics” (p.126).

Jobard et al.’s results are in accordance with the literature about the two routes to access words previously reviewed. In terms of brain areas, they found unexpected activation in the left precentral gyrus, which may be reflecting access to motor procedures required for uttering words in the context of silent reading. Analyses revealed that low span readers activate more areas involved in visual, phonological and semantic processing: the VWFA, precentral gyrus, mid part of the temporal sulcus, planum temporale close to the supramarginal gyrus, posterior part of the middle temporal gyrus (MTG) and the orbitalis part of the inferior frontal gyrus (IFG). Low spans relied more on dorsal visual regions, which may indicate a change from parallel to serial processing of visual input – participants may be decomposing the words in order to access them through a grapho-phonological reconstruction rather than through the orthographic-semantic route. Higher span readers rely less on the abovementioned regions; they generally activate only the regions implicated in the direct access to meaning from visual analysis of written words. In the authors' own words, "our results indicate that the grapho-phonological reconstruction of words may be achieved by recruiting additional cerebral regions to the ones enabling the lexical route when no direct link between orthography and semantics is available" (p.127). Finally, their findings show that the participant's proficiency in reading (WMC as measured by the RST) is a factor that plays a role in what route participants make use of while reading.

Prat and Just (2011) investigated the functional connectivity associated with processing demands in a reading task. Participants were divided into two groups: individuals with higher and lower working memory capacity. Results showed that individuals with higher working memory capacity exhibited higher efficiency, higher adaptability and better synchronization of the language neural networks than did the participants with lower working memory capacities in reading comprehension of sentences.

Taking into account all the topics and issues discussed in this section about reading processes, let us now turn to how words, concepts, representations are organized in the human brain.

2.2 WORDS IN THE BRAIN: HOW THE MENTAL LEXICON IS ORGANIZED

The question of how the human brain represents and organizes knowledge about words and concepts has been fascinating for a diversity of scientific communities: philosophers, psychologists, linguists, computational linguists, neuropsychologists, neuroscientists. Its significance lies at the core of cognition, in understanding how we make sense of the world, how we understand who we are. Researchers have applied different methods and techniques to explain how everyday concepts such as *apple, bird*, and *house* are represented in the human brain. This section is divided into three subsections. The first introduces key definitions, for instance, what words, concepts and the mental lexicon refer to. The second subsection familiarizes the reader with the most influential models of semantic memory and the third, presents a thorough review of studies on the neural bases of concepts and representations.

2.2.1 Words, concepts, mental lexicon: some key definitions

To be able to use and understand any word, we need to access the mental lexicon[14], a mental store of information about words that contains semantic information (words' meanings), syntactic information (how words combine to form sentences), and details about spelling and pronunciation (Aitchison, 1987). Such knowledge is part of semantic memory that includes the knowledge we share with other members of our culture about the world (Cabeza & Nyberg, 2000; Matlin, 2004; Binder & Desai, 2011), encyclopaedic knowledge, lexical, and conceptual knowledge. According to Barsalou (2008), our conceptual system refers to an extensive system - distributed all over the human brain - that represents knowledge organized in terms of categories about all aspects of human experience: objects, settings, events, agents, actions, affective and mental states. For him, our attentional system focuses on individual components of experience, classifying them into categories. For instance, our knowledge about the category *furniture*, or about the exemplar *chair*, develops from focusing attention on furniture or chairs across experiences, in such a way that we extract information about the different types and integrate the characteristics into a concept. Howard (1987) agrees that concepts are "generally *abstractions* from experience" (p.3) that "reduce the complexity of the world to manageable proportions" (p.1).

Nevertheless, what is a concept? Concepts are mental representations, ways of categorizing the world so that we can understand the world we live in and be able to communicate (Baddeley, 1990; Matlin, 2004). Howard (1987) explains that if we were not able to categorize the world into concepts, we would treat each situation, each stimulus as unique; we would have to start from scratch without being able to make generalizations, to identify patterns. Additionally, we would be tied to the immediate situation, being unable to use our past experience to evaluate the present one. In brief, "the world would be a confused, unanalysed set of stimuli" (Howard, 1987, p.3). As we proceed having different experiences, the borders of the concepts may be remodeled and new concepts may be formed (Paradis, 2004). As well, Kutas and Federmeier (2011) explain that conceptual representations are dynamically created and highly context dependent.

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[14]For an in-depth review about the mental lexicon, the reader is referred to Sousa and Gabriel's state-of-the-art article (2015).

For instance, teachers create categorizations so that the world, particularly a specific topic, makes sense to the students, like arts teachers who use the division of artistic styles in periods (Impressionism, Romanticism, Modernism, among many others) so that students understand the basic principles underlying those masterpieces.

In this context, can a word be considered a concept? Howard (1987) elucidates that “a word is not a concept. A word is a symbol that labels a concept” (Howard, 1987, p.18), although some authors make use of the term ‘concept’ as synonymous to ‘category’, ‘word’, and still, use the term ‘meaning’ to refer to the concept associated with a word. Moreover, the same concept may be named by different words, for example, *person* may be called as *human being*, *homo sapiens*, *member of the human race*. As well, the same word can name different concepts, a phenomenon termed polysemy, as the Portuguese word *manga* that can refer to the shirt sleeve or to a species of tropical fruit, and the English word *bank* that can refer to the side of a river or a money institution. In order to arrive at the meaning of these words, contextual information is needed. These examples demonstrate that “the conceptual level goes beyond our linguistic knowledge of words” (Gazzaniga, Ivry & Mangun, 2009, p.391).

Additionally, any particular stimulus may be allocated to different categories; for instance, a *house* may be considered a dwelling; a home; a haven; an obstacle; an investment; a national treasure. How we classify the stimulus on a given circumstance depends largely on our objectives and interests at the time. For instance, a *sparrow* may be categorized as a bird; an animal; a life form; a danger or a nuisance by certain breeders; nevertheless, ornithologists may classify it as an object of interest. Accordingly, Howard (1987) explains that “the world can be viewed in many different ways, according to each person’s set of concepts” (p.7). Cultural reasons and the places where people have grown up or have lived help shaping the way people think. Thus, concepts are idiosyncratic in nature.

Representations become activated through our own thoughts and intentions and through our perception of words and sentences, pictures, photos, events, objects, and states in real life. For example, when a person reads the word *apple*, the characteristics of it as color, shape, size, taste, and smell come to mind instantaneously. According to Barsalou (2008), the dominant view in cognitive science considers the conceptual system as “a modular memory store that contains amodal knowledge about categories” (p.92). On the other hand, the dominant view in cognitive neuroscience postulates that “categorical knowledge is grounded in the brain's modal systems rather than being represented amodally in a modular semantic memory" (Barsalou, 2008, p.92). For instance, our knowledge about *dogs* is represented in the visual form of how dogs look like; in the auditory form of how dogs make noise; and in the motor representations of how to interact with a dog. The controversy remains since both views receive empirical evidence, as we will see in the review that follows.

2.2.2 Models of the organization of semantic memory

It is commonsensical that the semantic memory system ought to be highly organized so that people can analyze, manipulate and search items, thus being able to cope up with the demands of processing input and producing language in real time. Searleman and Herrmann (1994) highlight that these processes are so automatic and happen effortlessly that people may not even be aware that they are performing such tasks. But how is semantic memory organized? How does the human brain represent and organize knowledge about concepts? Many scientific communities have been interested in such issues. According to Aitchison (1987), Mitchell and colleagues (2008a) and Just, Cherkassky, Aryal and Mitchell (2010), philosophers and psychologists have formulated theories to explain how simple concepts, as *apple*, *bird* and *dog*, are represented in the human brain. Linguists have characterized the different semantic roles associated with specific verbs; computational linguists have analyzed the statistics of large text corpora and have revealed that the meaning of a word is, to some degree, captured by the distribution of words and phrases in which it regularly appears. Psychologists have studied the meaning of words taking into consideration their defining and characteristic features. Researchers investigating the semantic effects of brain lesions and the semantic organization in healthy participants have added interesting data to the debate, which will be reviewed in the next section.

In this ambit, it is reasonable to think that the mental lexicon would not be organized the way a dictionary is. Having in mind the requirements of discourse processing in real time, individuals would not be able to access words in alphabetical order since it would take too long. According to Gazzaniga et al. (2009), some researchers have theorized that the mental lexicon must be organized conceptually as information-specific networks. As characteristics, the mental lexicon has no fixed content; we can forget words and learn new ones. Second, more frequently used words are more readily available (Anderson, 2010; Ellis, 2002); for example, *chair* is more quickly accessed than *hippopotamus*. Ellis (2002) explains "that language learning is exemplar based" (p.166), frequency[15] effects pervade all aspects of language processing. Third, auditory neighbors are identified more slowly, like *hate*, *late*, *rate* and *eight*. As figure 2.3 illustrates, Levelt (1989, as cited in Gazzaniga et al., 2009) hypothesizes that the lexeme level refers to the word forms whereas the lemma level refers to the grammatical properties and the semantic specifications of the word.

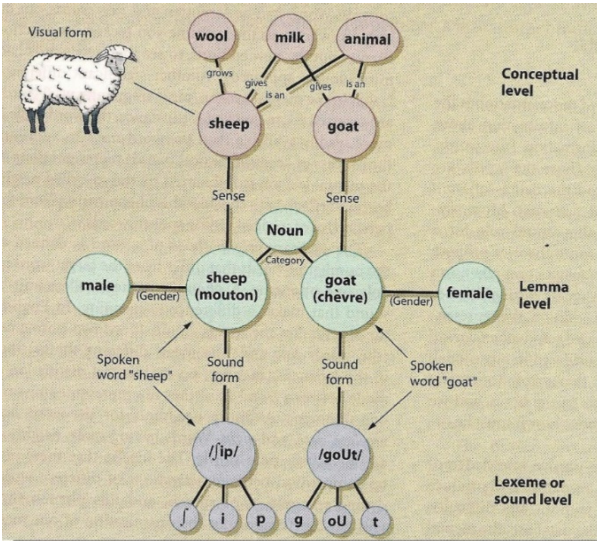

Figure 2.3. Fragment of a lexical network according to the Levelt's model. Scanned from Gazzaniga et al. (2009, p.390).

Gazzaniga and colleagues (2009) explain "this semantic specification defines the conceptual conditions under which it is appropriate to use a certain word" (Gazzaniga et al., 2009, p.390). It is suggested that the mental lexicon would be also organized in terms of the relations between words, for instance, *sheep* and *goat*, as they are related in meaning, they tend to be close in the network. Empirical

[15]Word frequency is the "measure of how frequently a word occurs in speech or text. A word's frequency of occurrence is usually determined on the basis of a word count of speech or text corpora" (de Groot, 2011, p.459).

evidence comes from semantic priming studies[16], but they will not be reviewed here due to space limitations and the scope of this review.

A variety of models have been proposed reflecting the uncertainty about how conceptual information is represented. According to Baddeley (1990) and Searleman and Herrmann (1994), in semantic network theories or network models, word meanings are hierarchically represented in a network of interrelated concepts. The concepts are arranged as nodes in the network, being each node associated with a number of properties. The more semantically related two words are, the closer the connection between them is. These models posit that "activation spreads from one conceptual node to others, and nodes that are closer together will benefit more from this spreading activation than will distant nodes" (Gazzaniga et al., 2009, p.391). As exemplified in Figure 2.4 next page, the node that represents the word *car* is close and has a strong connection with the nodes representing the words *truck* and *bus*. Conversely, the word *rose* would not receive activation when a person thinks about a *car*. This type of model predicts that hearing or reading a certain word should facilitate recognition of some words (closer in the network) in detriment of others, by means of spreading activation. The discussion becomes more complex when adding a second language, the topic of the next section.

[16]In semantic priming studies, subjects are presented with pairs of words, the first member of the pair, the 'prime', is a word and the second member, 'the target', can be a real word, a nonword or a pseudoword (Gazzaniga et al., 2009). If the target is a real word, it can be related or unrelated in meaning to the prime. In lexical decision tasks, participants are required to decide as quickly as possible whether the target word is a word. Participants are faster and more accurate when the target word is preceded by a related prime (for example, the prime *car* for the target *truck*) than an unrelated prime (as *tulip* for *truck*). In fMRI studies, a semantic priming effect is a decrease in the BOLD signal for repeated words (Bookheimer, 2002). By employing semantic priming paradigms, researchers concluded that the decrease in activation in the inferior frontal gyrus reflects its primary role in semantic processing.

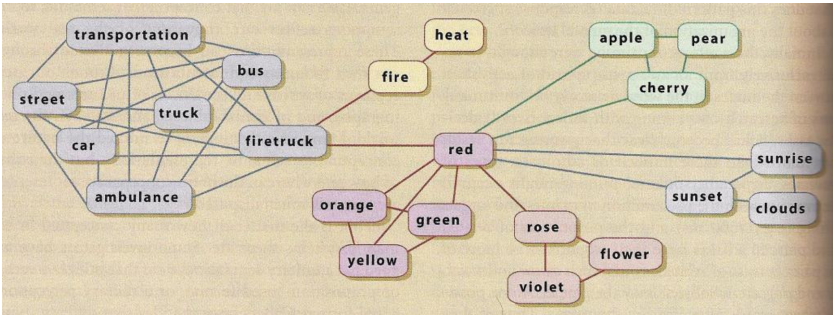

Figure 2.4. Example of a semantic network, as proposed by Collins and Loftus (1975, as cited in Gazzaniga et al., 2009, p.392).

Although the semantic-network model has been very influential in the literature, other models were proposed in the attempt to understand how concepts are represented. Feature comparison models suggest that concepts are represented by their semantic features or properties (Baddeley, 1990; Searleman & Herrmann, 1994). For instance, *bird* ‘has feathers’, ‘has wings’, ‘can fly’, ‘sings’, ‘has two legs’, ‘eats worms’, ‘is food for cats’. In this case, the defining feature of *bird* would be ‘has feathers’ and the other features would be considered characteristic features, since they apply to most members of the category but are not essential for distinguishing among other categories. According to Gazzaniga et al. (2009), these models are confronted with the problem of activation: “How many features have to be activated in order for a person to recognize a dog?” (p.392). In addition, it is not clear how many features would have to be stored. For instance, a *cup* could be ‘made of porcelain or plastic’, and we would recognize it in both cases, as ‘a recipient to drink coffee or tea’. Mervis and Rosch (1981) explain that there is a set of features - core features - that make, for instance, a dog a *dog*.

Despite such issues, feature-norming studies have been conducted to aid in the understanding of how words are organized and why some semantic classes are impaired, while others are not, in cases of brain lesions. In this type of study, participants are asked to list the characteristics associated with several words, revealing a set of essential features and suggesting a possible grouping of features according to sensory-motor modalities. Chang, Mitchell and Just (2011) explain that one way of characterizing an object is by asking what features this object brings to mind when people think about it. For instance, Cree and McRae (2003) asked participants to list the features of 541 concrete nouns. The features listed by the participants constitute the verbalization of actively recalled semantic knowledge. As an example, when looking at the stimulus *house*, commonly people report features like '*place to live in*', '*made of bricks*', '*made by humans*', among other features.

Rosch's research group conducted, in the decade of 1970, a series of experiments about categories, family resemblance among items of the same category, as well as about prototypicality, in other words, studies about how much some exemplars represent the idea or image of the category meaning. According to these studies, many exemplars of concepts vary in a continuum from typical to atypical (Howard, 1987), as in Rosch (1975), *orange* was considered a more typical example of fruit than *strawberry*. Rosch and Mervis (1975) suggested that "the more an item has attributes in common with other members of the category, the more it will be considered a good and representative member of the category" (p.582).

In this line, Rosch, Mervis, Gray, Johnson and Boyes-Braem (1976) demonstrated that some concepts represent basic level categories. As explained by the authors, people tend to refer to the basic level rather than to the superordinate level, for example, we use *car*, rather than *vehicle* or *means of transportation*; *television* rather than *furniture*; or *books*, rather than *toy* (Rosch, 1975). The basic level is the most general level at which (1) a person performs similar motor actions when interacting with members of the category; (2) category members have similar overall shapes; and (3) a mental image is able to reflect the entire category. To make it clearer, the concept *bird* is part of the taxonomy where above we have *animal, life form, thing* (superordinate levels) and below, *canary, hummingbird, pigeon* (subordinate levels). Usually, the superordinate level is considered to be too general and the subordinate level, too specific, the reason why studies point to a preference for basic level concepts. As explained by Howard (1987), these concepts are generally the first concepts learned on a taxonomy and they tend to evoke common behaviors, for instance, different types of *chair* tend to produce the same response (people sit on them), while different types of *furniture* (*bookcase, closet, table*) tend to produce different reactions.

Cree and McRae (2003) conducted a study that provided insights into how the information about 541 concepts of 34 categories is represented, organized and computed. Their behavioral study had as main goal "to uncover factors that can be explained in terms of both the specific processing responsibilities of distinct brain regions and the general processing characteristics of the brain" (p.163). They asked 30 participants, undergraduate students, to list features of 20 or 24 concept names such as *horse*, *desk*, and *car*. With all the data collected, the researchers derived a representation for each concept taking into account the features listed by at least 5 of 30 participants, in such a way that idiosyncratic responses were not considered. In the authors' words, "when participants call to mind features to list in the norming task, they directly tap into representations that have developed through repeated multisensory exposure to, and interactions with, the various objects" (p.167). They analyzed concepts from four domains: *creatures*, *nonliving things*, *fruits/vegetables* and salient exceptions as *musical instruments* and *foods* and concluded that each domain has characteristics that distinguish one from the others. *Fruit* and *vegetables* have high salience of visual-color, taste, tactile and encyclopedic features as well as in functions (people eat and prepare them). *Creatures* have many visual-motion features (they do many things on their own), visual-parts, surface properties and encyclopedic features; few function features (they serve few functions for people) and no made-of features (creatures are not made of something). *Nonliving things* are high in functions, visual parts, encyclopedic and made-of features and lower in visual-motion and visual-color features in their representations. *Foods* present high salience of tactile, taste, smell and encyclopedic features, making them cluster with *fruit/vegetables* (people eat them), and are low in visual-parts and surface properties. *Musical instruments* have a high number of sound features, relatively low function features and no visual-motion, taste or smell properties. The authors conclude that by extracting the knowledge types that differentiate among domains, it is possible to relate visual-motion information with creatures; functional information with nonliving things and fruits/vegetables; visual-color, taste, and tactile information for fruits/vegetables and food (Cree & McRae, 2003). Anderson (2010) agrees that "biological categories are more associated with perceptual categories such as shape, whereas artifacts are more associated with the actions that we perform with them" (p.143).

Behavioral studies have revealed much about the representation of concepts, "showing that people seem to consistently group together items that share perceptual and functional features in common and that often bring one another to mind" (Kutas & Federmeier, 2000, p.463). Linguistic cues, as written words, activate, in a matter of milliseconds, information from semantic memory; thus, facilitating our fast response to communication, to life in society (Binder & Desai, 2011). In Cree and McRae's words (2003), "People are amazed by the development of semantic knowledge in infants and troubled by its loss in debilitating conditions like dementia of the Alzheimer type, but for most of their adult lives, they simply take semantic knowledge for granted" (p.163). Now we turn to the literature related to brain lesions and neuroimaging to contribute to the discussion on the neural bases of concepts and representations, the topic of the next subsection.

2.2.3 The neural bases of concepts and representations

The neural bases of concepts and representations have been inspected through lesion studies and more recently through neuroimaging tools. According to Bookheimer (2002), the lesion deficit-approach has led to a large-module philosophy, that the language system is composed primarily of two domain regions: Broca's area (inferior frontal) and Wernicke's area (posterior superior temporal). Gazzaniga et al. (2009) elucidate that "different types of neurological problems create deficits in understanding and producing the appropriate meaning of a word or concept" (p.392). As Broca's is close to the primary motor area, lesions to this region involve impairment in "articulation, sequential production of speech, sentence production, syntax, naming, and comprehension of some complex syntactic structures" (Bookheimer, 2002, p.152). In turn, damage to Wernicke's results in great difficulty in comprehending speech and patients often use inappropriate words (for instance, *horse* when they mean *cow*) or nonexistent words (Springer & Deutsch, 1998). Gazzaniga et al. (2009) report that patients with deep dyslexia make comparable mistakes when reading (they might read *horse* where *cow* is written). Patients with semantic dementia have difficulty in assigning objects to a semantic category and frequently name a category when asked to name a picture (presented to a picture of a *horse*, they will say *animal*). Therefore, neurological evidence seems to support "the semantic-network idea because related meanings are substituted, confused, or lumped together, as we could predict from the degrading of a system interconnected by nodes that specify information" (Gazzaniga et al., 2009, p.393).

Studies with patients suffering from category-specific deficits have shown that semantic problems may be localized specifically to certain semantic categories, such as *objects* and *animals* (Bookheimer, 2002; Cree & McRae, 2003; Mahon & Caramazza, 2009; Gazzaniga et al., 2009). Researchers also reported cases in which patients had great difficulty in naming foods or living things when presented with a picture, though their naming of tools was preserved; and the reverse pattern was also observed. Cree and McRae (2003) argue that a great number of patients present patterns of deficits that cross domain boundaries as *living* versus *nonliving things*, making it questionable that semantic knowledge could be organized by domain.

From considering these observations, it is possible to conclude that there must be a correspondence between the sites of lesions and the type of semantic deficit. Gazzaniga et al. (2009) elucidate that typically patients whose impairment involves *living things* have lesions in the inferior and medial temporal cortex, and frequently these lesions extend anteriorly. The anterior inferotemporal cortex is close to areas responsible for visual object perception, thus being often recognized as the endpoint of the object recognition stream. The medial temporal lobe passes on information from the association cortex[17] to the hippocampus that, in turn, is vital for the encoding of information in long-term memory. Impairments for man-made things, like *tools*, involve damage to the left frontal and parietal areas, areas associated with motor processing. These areas seem to be implicated in the representation of actions, consequently, central for sensory-motor functions. These observations have led to the hypothesis that biological categories (*fruit, animals*) would rely more on physical properties or visual features, while *man-made* objects would be identified by their functional properties (Barsalou, 2008; Anderson, 2010).

Springer and Deutsch (1998) and Gazzaniga et al. (2009) report the findings from Damasio, Grabowski, Tranel, Hichwa and Damasio (1996) as compelling pieces of evidence for category-specific deficits. Such researchers found that brain damage in the left temporal pole correlated with problems in retrieving people's names; lesions in the anterior part of the left inferotemporal lobe with problems in naming animals; and damage to the posterolateral part of the left inferotemporal lobe along with the lateral temporo-occipitoparietal junction with problems in naming tools. Damasio and colleagues (1996), in their two PET studies with brain-lesioned patients and typical individuals, have suggested that the retrieval of concrete words depends not only on classic language areas but also on bilateral areas in higher-order

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[17]The association cortices include most of the cerebral surface of the human brain and are largely responsible for the complex processing that goes on between the arrival of input to the primary sensory cortices and the generation of behavior" (Purves et al., 2008, p.663). Lesion studies have suggested that the parietal cortex is important for attending to stimuli; the temporal cortex, for identifying the nature of stimuli; and the frontal cortex, for selecting and planning appropriate behavioral responses.

association cortices. For them, the conceptual networks are connected with the lexical networks in the left temporal lobe, and might be organized according to the physical characteristics of persons, animals and tools; as well as to the interactions people have with such entities.

In a nutshell, these cognitive neuropsychological studies of brain-lesioned patients suggest that the representation of conceptual knowledge is based upon perceptual and motor processes (Mahon & Caramazza, 2009) and provide evidence for the hypothesis that the brain stores semantic information in terms of categories (Bookheimer, 2002). Nevertheless, the investigation of brain lesions presents some limitations and results should be interpreted with caution.

Price (2010) reviewed 100 studies published in 2009 using fMRI to unveil the functional anatomy of speech comprehension and production in the healthy adult brain. As regards conceptual processing, the author found activation in "the same set of regions that have been associated with single-word comprehension" (p.78). These regions reflect the amodal semantic processing network involving the inferior frontal gyrus, ventral and dorsal medial prefrontal cortex, posterior inferior parietal lobe, middle temporal gyrus, fusiform, parahippocampal gyri, and the posterior cingulate gyrus.

According to Newman and colleagues (2003), neuroimaging studies on single word processing have implicated the pars triangularis of the IFG in semantic processing, the processing of meaning. Sirigu et al. (1998) compared syntax and script processing in patients with lesions in the pars triangularis and anterior extensions. These patients showed a great difficulty to produce a logical story narrative from a list of actions (script task), while their performance on a syntactic task (producing a grammatically correct sentence by assembling a list of phrases into a sensible order) was comparatively unimpaired. These results suggest that the pars triangularis is involved in semantic processing at the word level, but it is also involved in processing actions and their arguments, thus, it is involved in thematic processing, recognizing agents and patients.

According to Norman, Polyn, Detre and Haxby (2006), cognitive neuroscience seeks to deal with one of its most fundamental questions: the issue of representations. Questions such as (1) what type of information is represented in different brain structures; (2) how that information is represented; and (3) how that information is transformed at different stages of processing guide the studies of different groups throughout the world. The availability of neuroimaging techniques contributed to diversify how we can approach these issues. Norman et al. (2006) call attention to the use of multi-voxel pattern analysis (MVPA)[18] or multivariate analysis methods to study the representations of concepts in the brain. Studies with fMRI and MVPA methods have demonstrated that distinct spatial patterns in neural activity are associated with the task of viewing pictures and words of specific semantic categories, as *tools*, *buildings* and *animals* (Shinkareva et al., 2008; Just et al., 2010). These studies revealed that there are specific foci of activity in several brain regions for categories of concepts related to objects. These regions of focal activity may reflect the different dimensions concepts present: visual features, associations with object use, and associations with semantically related objects (Cree & McRae, 2003).

The variety of available approaches to investigate the representation of concepts – behavioral, brain lesion, functional neuroimaging – has resulted in a diversity of findings. According to Mitchell and collaborators (2008a), some theories postulate that word meanings are encoded in sensory-motor cortical areas, while other theories assume that word meanings are organized into semantic categories, such as *living* and *nonliving objects*. The authors point out to a lack of studies that seek to predict the specific brain activation produced when a person reads certain word and sees certain object.

Studies conducted by the group Marcel Just leads (*Center for Cognitive Brain Imaging* at *Carnegie Mellon University*, Pittsburgh, PA, USA) have investigated these questions with fMRI. Mitchell and colleagues (2003) proposed a method based on machine learning "to automatically classify the instantaneous cognitive state of a human subject, given his/her observed fMRI activity at a single time instant or time interval" (p.1). They made use of the data from a semantic category study in which participants were presented with words one at a time of twelve categories and their task was to press a button to indicate whether the presented word belonged to the category named. In addition, they used the data from a picture-sentence study in which participants were shown a sentence and a simple picture and then were required to answer whether the sentence correctly described the picture. The trained classifiers "successfully learned to decode the semantic category of a

[18]Multi-voxel pattern classification refers to an approach for pattern classification in fMRI data that "uses as its input data the relative changes in activation across a set of voxels" (Huettel et al., 2009, p.524). The reader may find more information about the technique in the Method chapter of the present work.

word based on the fMRI image" (p.3). Mitchell and collaborators (2004) expanded the scope of the 2003 work by adding data collected in a syntactic ambiguity study. Results confirmed the feasibility of the method to decode mental states from fMRI.

Mitchell and collaborators (2008a) present a computational model, trained with data from a large corpus that is able to predict with accuracy the brain activation associated with thinking about arbitrary concrete nouns for which there were not fMRI data available. The theory informing the study reveals that "the neural basis of the semantic representation of concrete nouns is related to the distributional properties of those words in a broadly based corpus of the language" (p.1191). The stimuli of the experiment were line drawings and their respective noun labels of 60 concrete nouns of 12 semantic categories. The whole set was presented six times randomly. Each stimulus was presented for three seconds, followed by a seven-second resting period in which the participants were instructed to clear their minds and fixate on an X displayed at the center of the screen. Besides, there were 12 extra presentations of the fixation, distributed across the session, for 31 seconds each to provide a baseline measure of activation (Mitchell et al., 2008b). Nine participants were required to think actively about the properties of each exemplar. To ensure that each participant would think about the same set of properties while each concept was presented, prior to the fMRI session, the participant would be invited to list the properties of each item (for instance, for the item *glass*, one can think of '*water', 'to drink', 'made of glass', 'made of plastic'*). Participants were free to choose any properties they wished, since there was no attempt to impose consistency across participants. The researchers trained a separate computational model for each participant using a set of 25 intermediate semantic features (verbs that reflect what individuals do with each of the 60 concrete nouns).

Considering these data, the researchers created and trained models. The fMRI images produced by the trained models could capture "substantial aspects of brain activation associated with stimulus words outside the training set" (Mitchell et al., 2008a, p.1193). Findings lend "credence to the conjecture that neural representations of concrete nouns are in part grounded in sensory-motor features" (p.1194). In part because the 25 intermediate semantic features exhibited significant activation in brain regions such as frontal areas, not directly associated with sensory-motor functions. Mitchell and colleagues argue that their study did not aim at revealing the neural activation of specific cortical regions associated with decoding a word; instead, it considered all cortical voxels involved so that computational models could be trained, from the data collected with participants, with the objective of determining which locations are modulated by which aspects of word meanings.

Shinkareva and colleagues (2008) examined the ability to identify the cognitive state associated with viewing a line drawing of 10 familiar objects: 5 tools (*drill, hammer, screwdriver, pliers* and *saw*) and 5 dwellings (*apartment*, *castle*, *house, hut* and *igloo*). Participants were required to perform the same task as in Mitchell et al. (2008a). Results show, for the first time in the literature, the ability to identify individual objects and the category of the object the participant was looking at based on other participants' activation patterns. Findings indicate that

> there is an identifiable neural pattern associated with perception and contemplation of individual objects, and that part of the pattern is shared across participants. This neural pattern is characterized by a distribution of activation across many cortical regions, involving locations that encode diverse object properties (Shinkareva et al., 2008, p.7)

Shinkareva, Malave, Mason, Mitchell and Just (2011) enlarged the 2008 study by adding the presentations of words. Findings point to an association of the neural representations of words and pictures related to *tools* and *dwellings*. In the authors' words, "it is the first demonstration of the ability to identify a word category on the basis of activation generated by picture stimuli, and vice versa" (Shinkareva et al., 2011, p.2422). This common neural representation indicates that words and pictures "share a feature-based, distributed, conceptual representation marked by several interesting properties" (p.2424).

Shinkareva, Malave, Just and Mitchell (2012) conducted an exploratory study with the fMRI data collected in the 2008 study that revealed the extent to which the internal representation of individual concepts related to *tools* and *dwellings* and their mutual similarity are shared across participants. First, the researchers examined how similar the internal representation of objects was across participants and then they studied the object structure common to all participants. Twenty-five anatomical regions "contained adequate information for meaningful object category identification on average across participants" (p.1379) and the regions with highest accuracies were "the bilateral primary and secondary visual areas, cerebellum[19], parietal and posterior temporal areas, and left frontal areas: inferior, superior, and precentral gyri and insula" (p.1380). Findings indicate a commonality in the internal representation of *tools* and *dwellings* and that part of the variability can be explained by the category structure of the objects. The authors highlight that their exploratory study "opens possibilities for future investigations of individual differences in representations" (p.1381).

The study carried out by Just and colleagues (2010) revealed the discovery of the key semantic factors underlying the neural representation of concrete nouns, in addition to relating these semantic factors to specific brain anatomical locations. Although the experimental design is the same used in Mitchell and collaborators (2008a), this study reports the neural representation evoked only by words (no pictures) and reveals "the component building blocks of the brain's representation of the meaning of physical objects" (Just et al., 2010, p.2). The words loaded in the following semantic factors: *shelter*, *manipulation,* and *eating* as well as one factor related to the visual features of the printed word: the *word-length* factor.

As regards the locations, two factors (*eating* and *manipulation*) were strongly left-lateralized, probably due to the participants' handedness, whereas the *shelter* and *word length* factors activate clusters in both hemispheres. Figure 2.5 in the next page reveals the voxel clusters associated with the factors. *Shelter* (*apartment, car*) activates the bilateral precuneus[20], bilateral fusiform

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[19]The cerebellum has traditionally been viewed as the coordinator of motor function and only recently has been associated with cognitive and affective processing. De Smet, Paquier, Verhoeven and Mariën (2013), in their state-of-the-art article about the role of the cerebellum in higher cognitive functions, explained that lesion studies have connected cerebellar damage with syntax impairment, and that some neuroimaging studies have associated cerebellar activation with verbal fluency and lexical retrieval. Murdoch (2010) in his review about the role of the cerebellum in language suggests that it is involved "in the modulation of a broad spectrum of linguistic functions such as verbal fluency, word retrieval, syntax, reading, writing and metalinguistic abilities" (p.866).

[20]The precuneus has "traditionally received little attention, mainly because of its hidden location and the virtual absence of focal lesion studies" (Cavanna & Trimble, 2006, p.564). Recent neuroimaging studies have suggested a central role in a wide spectrum of tasks, such as visuo-spatial imagery, episodic

gyrus/parahippocampal gyrus and the left inferior temporal gyrus. *Manipulation (screwdriver, key*) activates left-hemisphere areas: the postcentral and supramarginal gyrus, the inferior temporal gyrus and the precentral gyrus. In addition, *eating (lettuce, glass*) activates left-hemisphere areas: the inferior and medial frontal gyrus and the inferior temporal gyrus. *Word length (butterfly, telephone*) activates the occipital pole and the lingual/fusiform gyrus bilaterally, including the VWFA. In the authors' own words, the factor "captures an essential part of the representation of a written word as it progresses into the semantic system" (Just et al., 2010, p.6). Therefore, one may conclude that the neural representations of concepts involve multiple brain areas specialized for various types of information.

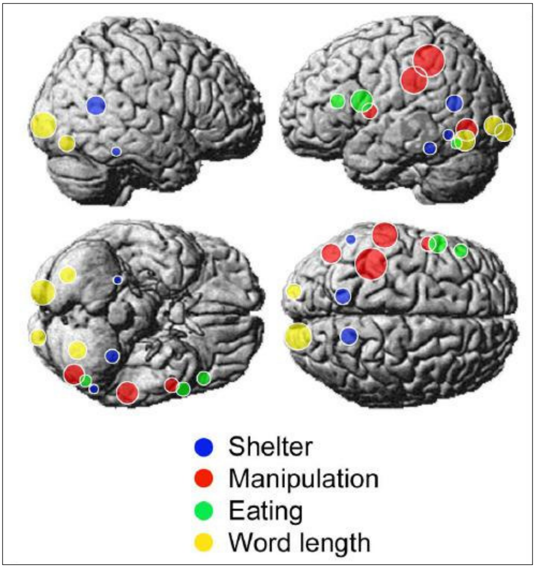

Figure 2.5. Locations of the voxel clusters (spheres) associated with the four factors. Scanned from Just et al. (2010, p.7).

The neurosemantic theory proposed by Just and colleagues (2010) includes (1) the accurate identification of the thought generated by a concrete noun based on the underlying brain activation pattern; (2) the commonality of the neural representation of concrete nouns across

memory retrieval, self-processing operations, as first-person perspective taking and the experience of agency, as well as the modulation of conscious processes.

people; and (3) the ability to predict the activation pattern for a noun previously not seen based on the model of the content of the representation.

A recent study conducted by Zinszer, Anderson, Kang, Wheatley and Raizada (2015) revealed that two independent groups of native speakers of two different languages, English and Chinese, share the same concepts. Participants were given seven monosyllabic words (*axe, broom, gown, hoof, jaw, mule* and *raft*) in English and their translation equivalents in Chinese. By applying MVPA methods, the researchers could translate the words between the two languages with 100% of accuracy, only based on the patterns of functional activity such words elicit in the brain. The authors conclude that "these conceptual representations are grounded in multimodal somatosensory and episodic memories" (2015, p.5).

From the exposed, it seems reasonable to conclude that semantic properties of words are crucial for understanding the differences in the topography of brain activations (Pulvermüller, 1999). Results seem to follow an *embodied cognition* perspective, that "conceptual representations contain perceptual and motor components corresponding to human interactions with real entities in the physical environment" (Shinkareva et al., 2012, p.1381). In addition, Pulvermüller (1999, p.266) acknowledges that valence, "the degree to which the stimulus is evaluated as positive or negative", can influence brain processing. In general, emotion-related words evoke activity in the limbic system[21]; action words, in the fronto-central cortex; and object words, in the inferior-temporal region (Pulvermüller, 2012).

In a nutshell, the application of neuroimaging techniques to investigate the neural representation of concepts has been revealing the existence of semantically organized networks activated during the perception of objects as well as demonstrating a degree of commonality across people in the semantic organization of concrete nouns (Mitchell et al., 2008; Just et al., 2010; Shinkareva et al., 2012). Several studies have been conducted and we have considerable knowledge about the cerebral organization of concrete nouns in an L1. In spite of the great number of studies about the neural representation of concepts in

[21]Subcortical structures and parts of the cerebral cortex form the limbic system. Cortical regions include the insula, the orbital frontal cortex, subcallosal, cingulate and parahippocampal gyri. Subcortical structures include the olfactory bulb, hypothalamus, amygdala, septal nuclei and some thalamic nuclei (Swenson, 2006).

monolinguals, much less is known about it in bilinguals, the topic of the next section.

2.3 BILINGUALISM

Those who know many languages live as many lives as the languages they know. (Czech proverb)

Bilingualism is a worldwide phenomenon (Grosjean, 2012). As the world becomes more interconnected, it seems that bilingualism is "the rule and not the exception" (Bialystok, Craik, Green & Gollan, 2009, p.89). Some countries like the U.S.[22] support bilingual populations mainly because of the cultural and linguistic diversity of its citizenry. In addition, increased possibilities of moving around the globe have enlarged the number of individuals who have become bilingual. Nonetheless, what does it take to be considered a bilingual? Schwartz and Kroll (2006) define as bilinguals the individuals who actively use two languages to some degree of proficiency and explain that they rarely tend to be "equally proficient or balanced in their use of the two languages, rendering one of the languages the more dominant language" (p.968). Researchers as Grosjean (2012) define bilinguals as "those who use two or more languages (or dialects) in their everyday lives" (p.4). Additionally, bilinguals do not form a homogeneous group; they vary along a number of dimensions: age and manner of acquisition, level of proficiency and how much and in what contexts they use their languages.

Grosjean (2012) explains that "bilinguals usually acquire and use their languages for different purposes, in different domains of life, with different people. Different aspects of life require different languages" (p.29). Depending on the situation, bilinguals stay at the monolingual

[22]Not as much as in Europe or in Asian and African nations, the United States is a country with many bilinguals. According to Grosjean (2012), the country had an estimated number of 55 million bilinguals in 2009. In Brazil, I could not find numbers or estimates of the bilingual population. In spite of that, results from the last census (IBGE, 2010) show that among the indigenous community, there are 274 different languages spoken. In addition, Grosjean (2012) cites in his book the case of German-Portuguese bilingualism in Pomerode, Santa Catarina, Brazil. More recently, Brazil has been attracting immigrants from Haiti and African countries who look for job opportunities and better life conditions. Therefore, there are reasons to believe that there is an expressive number of bilinguals in Brazil.

end of the continuum or move right along the continuum, choosing different points on it. For instance, when I was living in the U.S. during my PhD internship (*sandwich program*), I used English to talk to people at the university (one end of the continuum), Portuguese when hanging out with Brazilians (another end of it), and a mixture of Portuguese and English when talking to Portuguese people (moving along it). Currently that I am living back in Brazil, I use English during the major part of my day due to my studies, but I speak Portuguese when I interact with people. However, when I am at UFSC, I speak both Portuguese and English depending on whom I am talking to, the topic, and the situation. As illustrated, movement along the continuum occurs whenever there is a need for it.

Bilinguals may be dominant in one of their languages or balanced. However, the notion of language dominance is difficult to define. Some scholars consider it being based on fluency; some, on fluency and use; and others, on the ability to read and write in the language. The majority of researchers emphasize fluency. In the literature, it is possible to find subjective fluency, when the participants self-report their fluency on the languages in a background questionnaire; and objective fluency, when the researchers evaluate participants' fluency through assessment tools, sometimes devised by the researchers and evaluated by raters, and sometimes by using standardized proficiency tests. Furthermore, bilinguals may not develop total and equal fluency in all language skills (speaking, listening, reading, and writing) and their language repertoire may change over time.

Experimental research has suggested that both languages of a bilingual are jointly activated even when the context does not require the activation of both (Marian et al., 2003; Grosjean, 2012). Grosjean (1998) proposes the concept of language mode as "a state of activation of the bilingual's languages and language processing mechanisms" (p.136). He explains that in most of the psycholinguistic studies, "the bilinguals were probably not in a monolingual mode when they were tested" (p.138). In case of studies about the representation of the bilinguals' languages, he recommends researchers to put their participants in a *language set* by providing them with instructions in one of the languages, doing the preliminary tasks in that language, talking to them in that language, and by giving them monolingual stimuli. Thereby, researchers do not run the risk of having variable data because participants were placed somewhere along the monolingual-bilingual continuum.

Keeping in mind the fact that a monolingual adult has knowledge of about 50,000 up to 100,000 words (Balota & Coane, 2008; Libben, 2008) and is capable of recognizing and producing three words per second without any difficulty (Gazzaniga et al. 2009), bilinguals are thought to have at least twice this number of words in their lexicons if their combined vocabulary is taken into account. Because of the complexity of factors involved in bilingualism, the inner workings of the bilingual mind/brain have been intriguing philosophers and researchers for a long time. Puzzles remain as studies produce conflicting results (Grosjean, 1998). One of the central questions in bilingualism research concerns how the bilingual's languages are stored in memory: does each language have its own memory store or do the languages share a single system for representation? (Dufour & Kroll, 1995; Bialystok et al., 2009). Another crucial question refers to what extent bilinguals activate common cortical areas when processing L1 and L2 (Paradis, 2004). These two issues are the topic of the next subsection: studies on bilingualism.

Studies related to the teaching of languages have been interested in disentangling the factors involved in the success of learning languages. Paradis (2004) hypothesizes that speakers who have learnt an L2 after an early age will compensate for gaps in their procedural knowledge by relying more extensively on declarative knowledge. He acknowledges that the degree of motivation in learning the L2 influences the level of success in the use of the language. Saidi and colleagues (2013) is the first longitudinal study to document the changes in functional connectivity associated with vocabulary learning in L2. The participants were adults, who had already passed the critical period[23] to acquire a language. Results indicate that "language proficiency modulates functional integration levels within contributing circuits in L2 vocabulary learning" (Saidi et al., 2013, p.63). This finding corroborates the general law of activation changes during language development cited by Sakai (2005), that "cortical activations increase initially at the onset of acquisition, followed by the maintenance of the activations and then a fall in activations during consolidation of linguistic competence" (p.818).

[23]According to De Groot (2011), the *critical period hypothesis* claims that there is an ideal age during which it is possible to acquire a language, be it L1 or L2, to nativelike levels. Hernandez and Li (2007) define critical periods as "time windows within which learning outcomes are optimal and after which the ability to learn drastically decreases" (p.639). Notwithstanding, there is little agreement in the literature as to until which age that critical period takes place.

Studies have suggested that learning a foreign language, even in adulthood, changes the structure of language-related brain areas. Mårtensson and colleagues (2012) suggested that “adult foreign-language learning is accompanied by increases of gray matter volume in language-related brain regions. Plasticity of the hippocampus and the left superior temporal gyrus (STG) might be important for learning a new language” (p.244). Mechelli and collaborators (2004) found “an increase in the density of grey matter in the left inferior parietal cortex of bilinguals relative to monolinguals, which is more pronounced in early rather than late bilinguals” (p.757). In addition, the density in this region increases with proficiency level (PL), although it decreases as age of acquisition (AoA) increases.

A very recent study conducted by Pliatsikas, Moschopoulou and Saddy (2015) shows that the “everyday handling of more than one language functions as an intensive cognitive stimulation that benefits specific language-related brain structures” (p.3-4). They scanned, with fMRI and DTI (diffusion-tensor imaging), 20 late bilinguals (L2 speakers of English; AoA: 11) and 25 native speakers of English. They found that being a bilingual affects the structure of white matter tracts of the brain and, they believe, helps preserving its integrity in older age.

Bialystok, Craik and Luk (2012) view bilingualism as language experience, but for them, “managing attention to two or more languages imposes demands on the cognitive system that require brain regions not typically used for language processing” (p.245). Although bilinguals’ verbal skills in each language are generally weaker (than those of monolinguals of each language), fluent bilinguals seem to activate both languages simultaneously or at least display some kind of interaction between the languages at all times, “even in contexts that are entirely driven by only one of the languages” (p.241). As benefits, bilingualism enhances, at no matter what age, cognitive control; protects against age-related cognitive decline; and may postpone the onset of symptoms of dementia. Undoubtedly, being bilingual leaves marks on our brains: structural areas and connections are changed with language use, an evidence of neuroplasticity (Bialystok et al., 2009; Bialystok, 2011; Grosjean, 2012).

In a nutshell, “the bilingual is an integrated whole who cannot easily be decomposed into two separate parts. The bilingual is not the sum of two (or more) complete or incomplete monolinguals; rather, he or she has a unique and specific linguistic configuration” (Grosjean, 2012, p.75). That is the reason why bilingualism constitutes a fertile area for research. Whereas psycholinguistic models of the bilingual mental lexicon have focused on which level of representation – orthographic/phonological, lexical or conceptual level – the bilingual's languages are interconnected (Isel et al., 2010), neuroimaging studies have focused on investigating how language takes place in the brain. Vaid and Hull (2002) recommend researchers to investigate issues related to whether the processing of non-native languages recruits additional or fewer brain regions as compared to the processing of the native language. A great number of studies involving speaking, listening and reading have been conducted at the word level; a scarce number at the sentence level; and an even smaller number at the discourse level. The present section is divided into four subsections. The first presents the reader with the psycholinguistic models of the bilingual lexicon. The second and third subsections review neuroimaging studies about the bilingual language representation, on the word- and sentence-level, respectively. The fourth and last subsection presents a review on the scarce number of neuroimaging studies comparing the bilinguals' brains with the monolingual's ones.

2.3.1 Models of bilingual word representation

Although the separate storage model postulates two separate language-specific representational systems, research on language representation in bilinguals (as Dong, Gui & MacWhinney, 2005; Isel et al., 2010) has been suggesting that the languages known by a bilingual are connected conceptually. Kroll, Michael and Sankaranarayanan (1998) hypothesize that, on the one hand, languages differ lexically and syntactically, but on the other hand, the meaning each language conveys in words and sentences is shared across languages. Therefore, at the level of words, each language may possess a distinct lexicon; and at the level of concepts, "words in each of the bilingual's languages are thought to map to share meaning representations" (p.367).

Schwartz and Kroll (2006) explain that a variety of models have been proposed to explain how the bilingual mental lexicon is organized. In such models, there is a hierarchical organization of words and concepts. The *Word Association* model postulates that "L2 words access meaning indirectly via the L1"; L2 words are represented in the bilingual's mind as the translation equivalent in L1 (L2 word-L1 word meaning). The *Concept Mediation* model proposes that "L2 words have direct access to their respective meanings" (L2 word-L2 word meaning) (p.969). Figure 2.6, next page, presents the *word association* model on the left and the *concept mediation* model on the right. Potter, So, Von

Eckardt and Feldman (1984) published both models.

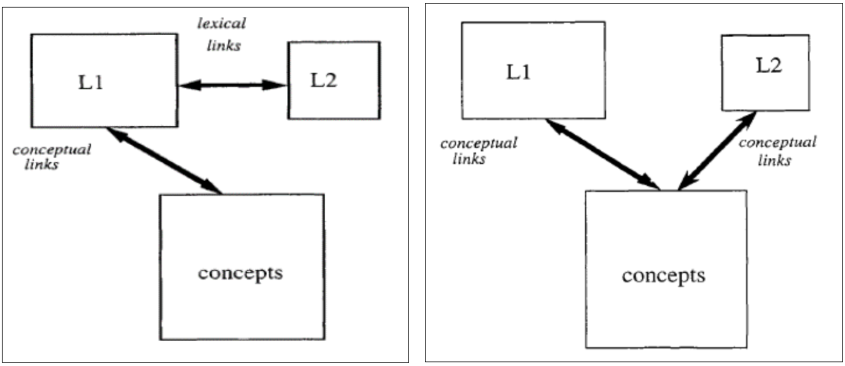

Figure 2.6. The *word association* and the *concept mediation* models. Scanned from Kroll et al. (1998, p.368)

These models do not accommodate the asymmetries in translation performance by bilinguals who learnt the L2 after early childhood and the ones for whom the L1 remains the dominant language (Schwartz & Kroll, 2006). The *revised hierarchical* model (RHM), proposed by Kroll and Stewart (1994), integrates the previous two models and is able to account for changes in connections between words and concepts as L2 acquisition develops. The RHM assumes, in the lexical level, that “the connection from L2 to L1 is stronger than the connection from L1 to L2” (Schwartz & Kroll, 2006, p.971) due to the stage in which learners use L1 translations to retrieve the meaning of L2 words. Therefore, L1 connections to concepts are stronger than the ones for L2, but the model acknowledges that as proficiency in the language increases, the L2 links to concepts begin to become similar to those for L1. As the *concept mediation* model, the RHM accounts for the possibility of skilled bilinguals accessing concepts directly through L2 words. Evidence for the RHM comes from translation experiments and semantic categorization tasks (Dufour & Kroll, 1995). It is the first model to account for the changes in mental representation during second language acquisition.

Another model, the *distributed conceptual feature* model agrees that concepts are shared across languages (de Groot, 1992, as cited in Kroll et al., 1998). The model comprises independent lexical representations for L1 and L2 that are “associated with concepts consisting of bundles of features” (p.372). Such conceptual features are shared across languages, although the particular features activated by a word and its translation are not essentially the same. Kroll and colleagues recognize that concrete words present more feature overlap across languages than abstract words, which are more culturally bound. It does not mean that abstract words and their translations do not overlap in meaning; the model predicts that fewer features overlap in the translation of abstract than of concrete words. Figure 2.7 presents, on the left, the *revised hierarchical* model and the *distributed conceptual feature* model on the right side of the page.

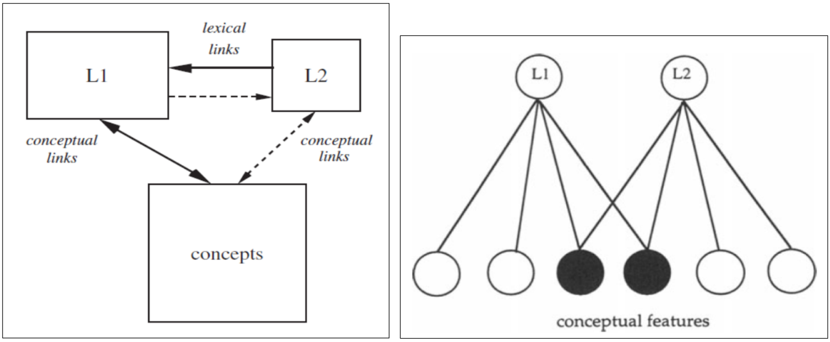

Figure 2.7. The *revised hierarchical* model (on the left) and the *distributed conceptual feature* model (on the right). Scanned from Schwartz and Kroll (2006, p.971) and Kroll et al. (1998, p.373), respectively.

Empirical findings from word recognition studies suggest that "bilingual word recognition involves the parallel, non-language-selective activation of both languages" (Schwartz & Kroll, 2006, p.975). It means that both languages are automatically activated as well as multiple entries may be activated simultaneously (Van Assche et al., 2012). A connectionist model put forward by Dijkstra and colleagues (1998, as cited in Schwartz & Kroll, 2006) called BIA (*Bilingual Interactive Activation*) contains four levels of representation nodes: letter features, letters, the orthographic forms of entire words, and language information. In this model, when a word is presented, the features of the constituent letters are activated; these features activate the letters that are part of the presented words and inhibit the letters that do not contain such features. In turn, activated letter nodes activate or inhibit word nodes in both languages the bilingual speaks. Lastly, activated word nodes transmit activation to the language node of the corresponding language.

In 2002, Dijkstra and Van Heuven updated the model to accommodate phonological and semantic lexical representations, creating the *BIA*+ model (as cited in Schwartz & Kroll, 2006). The model includes two subsystems: lexical identification and task schema. BIA+ predicts that during word identification visual input activate sublexical orthographic and phonological representations, which simultaneously activate lexical orthographic and phonological representations as well as semantic representations and language nodes. The language nodes function as language tags, indicating to which language an entry belongs to, hence displaying a representational role. The task schema subsystem controls which actions have to be performed for the task at hand based on the information that becomes available after lexical identification processing. Non-linguistic context affects the task schema system while linguistic information affects the identification system. Figure 2.8 presents the visual schema for both models. They have been receiving empirical evidence from semantic priming studies (Schwartz & Kroll, 2006).

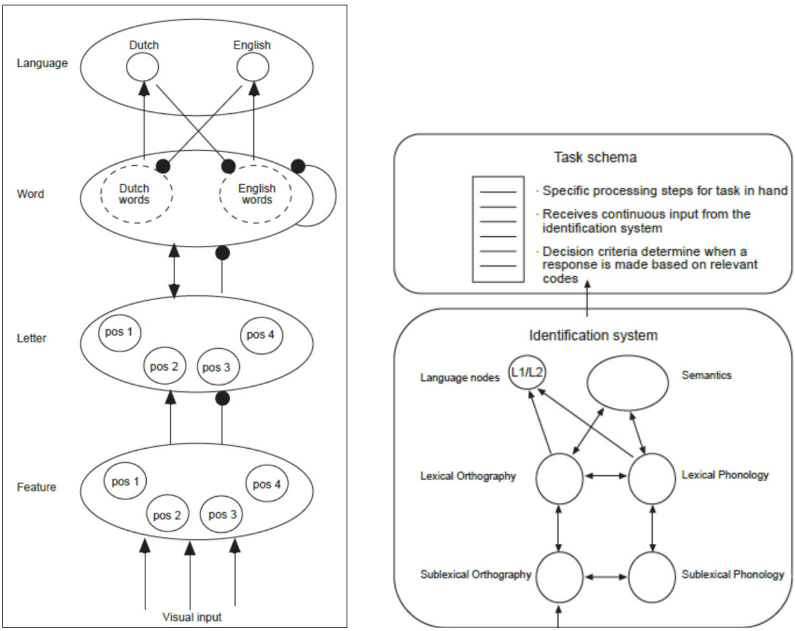

Figure 2.8. The *BIA* model (on the left) and the *BIA*+ model (on the right). Scanned from Dijkstra and Van Heuven (2002, p.177 and p.182).

Overall, there is a consensus in the area that L1 and L2 words are represented in an integrated lexicon and that lexical representations in both languages of a bilingual are activated when reading in one language (non-selective access). Studies with words in isolation, the topic of the following subsection, have been conducted confirming such findings. The next subsection reviews studies conducted at the word level, taking into consideration variables as age of acquisition (AoA) and proficiency level of bilinguals.

2.3.2 Word-level neuroimaging studies

The models explained in the previous subsection do not make a distinction between early and late bilinguals. As Perani (2005) argues, the acquisition of an L2 is a dynamic process that requires the recruitment of additional neural resources under specific circumstances. She clarifies that the differences in L1 and L2 representations are "related to the specific computational demands, which can vary according to the age of acquisition, the degree of mastery and the level of exposure to each language" (2005, p.211). A number of studies indicate that concepts in L1 and L2 are represented in the same brain regions (Illes et al., 1999), independently of age of acquisition (Fabbro, 2001) for proficient bilinguals (Balota & Coane, 2008) while others consider age of acquisition as an important factor to be taken into consideration (Kim et al., 1997). According to Marian and colleagues (2003), some studies have suggested "distinct non-overlapping cortical representations of the two languages in bilinguals" (p.71), but empirical findings seem to be more consistent with the hypothesis that the semantic level is shared among languages, at least for proficient bilinguals, since they seem to have the processes for L2 more automatized. For the authors, "it seems that a better posing of the question is not whether the bilingual lexicon is language-specific or shared, but what is the degree of this interaction and overlap, and what factors influence it?" (Marian et al., 2003, p.80).

Recent studies have contributed to the understanding that "the connections between words in L2 and the semantic representations of the first language (L1) strengthen as proficiency in L2 increases" (Buchweitz et al., 2012, p.282). The authors point out that the age at which words are learned in the L2 influences the strength of the semantic representations. As stated by Saidi et al. (2013), neurocognitive studies on bilingualism focused on the neural basis of L2 processing as a function of age of acquisition (AoA) and proficiency present controversial findings. Some authors sustain that age of acquisition determines functional organization of the L1 and L2 in the brain, while others claim that proficiency is more important than age of acquisition (Abutalebi, Cappa & Perani, 2001). Considering these variables, this subsection reviews 11 neuroimaging studies about word-level processes in the bilingual brain with different pairs of languages, with a focus on reading comprehension rather than listening comprehension studies.

To test whether there is any kind of difference in the representation of words due to AoA, Isel and colleagues (2010) inspected with fMRI whether French and German share a common conceptual system and share the same underlying neural representation in a group of 10 early and 10 late bilinguals. Early bilinguals were considered the ones who have been exposed to the two languages at the same time before the age of 3 years (natural setting). Participants performed a semantic categorization task involving 120 concrete nouns (the set of nouns were not provided in the article). Findings support the hypothesis that L1 and L2 share a common space of conceptual representations irrespectively of age of acquisition. The researchers found differentiated patterns of amplitude and localization in semantic representation of words as a function of L2 age of acquisition. While early bilinguals showed larger effects in the left superior temporal gyrus, bilateral superior frontal gyrus and the right posterior insula, late bilinguals showed larger effects in the left mid-insula and the right middle frontal gyrus. Such results suggest that “the attainment of lexical knowledge in L2 is possibly affected by neural maturation” (p.179).

Jamal and colleagues (2012) conducted a study with 12 early proficient Spanish-English bilinguals to investigate single-word processing in both languages. By early bilinguals, the authors meant that their participants learned the L2 before the age of 6. They used a silent reading task in which participants had to decide whether the words presented tall letters or false font strings. As results, they found that the L1 recruited the left inferior frontal gyrus (IFG) and the left middle temporal gyri (MTG) whereas the L2 activated the left IFG, the left middle frontal and the fusiform gyrus extending to the inferior temporal gyrus and the right MTG extending to the superior temporal sulcus. They concluded that single-word processing recruits the classical language areas associated with reading, although there are language-specific differences that may be related to the discrepancy in orthographic transparency.

In a very recent study, Hernandez and colleagues (2015) examined the neural correlates of lexical processing with a silent single-word reading task in early L2 learners. Two groups of Spanish-English bilinguals were investigated: 20 adults (with 18-26 years of age) and 21 children (with 8-13 years of age). The purpose was to scrutinize the transition from L1 dominance in childhood to L2 dominance in adulthood. As results, both groups activated a bilateral but left dominant set of areas, but the adult group recruited more the bilateral MTG relative to the children group. The authors suggested that this difference might be an indicator of fluent reading, the "difference in the brain that distinguishes adults from children when reading" (p.15). They acknowledge that such activity in the right hemisphere (RH) might indicate that adults were engaging in higher-level language processing. However, it has to be taken into consideration that it may be hard to encounter higher-level language processing in a single-word reading task.

Meschyan and Hernandez (2006) studied how language proficiency and orthographic transparency modulate neural activity in a bilingual single-word silent reading task. Twelve early Spanish-English bilinguals were recruited and according to the proficiency assessment conducted, they were more proficient in their L2 than in their L1. The researchers found that the less proficient language (L1) elicited slower reading times and required greater articulatory motor effort. Additionally, more transparent words in the L1 produced greater activity in the left superior temporal gyrus (STG), an area traditionally associated with phonological processing. More opaque words in the L2 elicited greater activity in occipital and inferior parietal visual areas.

To clarify the effects of proficiency, Tatsuno and Sakai (2005) investigated the developmental process in mastering an L2 in two groups of Japanese-English bilinguals. Fourteen age 13 bilinguals composed the first group, while fifteen age 19 participants, the second group. Both groups have the age of 12 as their AoA, the difference lying in the period these groups are learning the L2. The age 13 group was learning the L2 for approximately 8 months, while the age 19 group, for approx. 6 years. To perform the task, age 13 group participants received two months of classroom training in the L2 past tense. The task involved silent reading and production of regular and irregular verbs in English and verbs written in the *hiragana* and *kanji* writing systems of Japanese. The objective was to clarify the contribution of the left prefrontal cortex. As findings, the researchers observed less activation in the left dorsal triangular part of the IFG and in the triangular and orbital parts of the left IFG for the irregular past tense of English in higher proficient (older) participants. Additionally, they observed no activation in such regions for the L2 regular past in higher proficient participants, although the less proficient participants (age 13 group) displayed more activation in these areas for the L1. In the authors' own words, such results "suggest that the left IFG subserves language-specific functions that are critically required when mastering any language" (p.1637).

Marian and colleagues (2003) also found differences in brain activation for L1 and L2. They investigated 6 late fluent Russian-English bilinguals that started learning the L2 when they were 17 years old. In the paper, no assessments of proficiency were reported. The task involved reading and listening to L1 and L2 words and nonwords. Findings point to the similarity in brain regions activated for both languages, though differences within such regions across languages and levels of processing exist. The IFG was active in phonological and lexical processing whereas the STG was active only in phonological processing. Besides, the L2 elicited greater activation than the L1.

Yang and colleagues (2011) controlled for proficiency level to investigate the lexical representation of nouns and verbs in 16 late Chinese-English bilinguals who learned the L2 after the age of 12. Participants performed a lexical decision task while silent reading words. A large set of overlapping areas was activated, but processing the L2 seemed to rely on a more widely distributed set of areas than the processing of the L1. This set of areas include RH regions as the middle frontal, insula, angular gyrus and the bilateral superior parietal lobes. As no neural differentiation of nouns and verbs took place in the L1 and little differentiation in the L2, the authors suggested "the use of native language mechanisms for the processing of second language stimuli" (p.674).

To my knowledge, Illes and colleagues' study (1999) was the first to examine with fMRI whether semantic processes in L1 and L2 are mediated by a common neural system in late bilinguals with a word-reading task. Participants, 5 Spanish-English and 3 English-Spanish fluent (self-reported) bilinguals who acquired the L2 after the age of 10, read words while being scanned. They had to perform semantic decision tasks: to decide whether the presented words were concrete or abstract as well as decide whether letters were printed in uppercase or lowercase (nonsemantic decision). As findings, semantic judgments led to greater activation (than nonsemantic ones) in the left IFG for both L1 and L2 words. In addition, there was consistent LH activation overlap for both languages and some participants showed RH activation for both languages. Such results indicate that bilinguals present a shared frontal lobe system for semantic analysis, thus, "the two languages of a bilingual person access a common semantic system" (p.347).

In the same vein, Crinion and collaborators (2006) investigated with PET and fMRI how the bilingual brain distinguishes and controls which language is in use. In the PET study, 11 fluent late German-English bilinguals participated. In the fMRI study, 14 fluent late German-English bilinguals and 10 fluent late Japanese-English bilinguals took part. Both groups had their proficiency tested with a set of standardized tests and performed, inside the scanners, a task in which they had to read word pairs ignoring the first word and making a semantic decision based on the meaning of the second word. As results, the researchers found overlapping activation for all the languages. They also reported left caudate activation when changes in the language or the meaning of words appeared. They interpreted the left caudate as having a universal role in monitoring and controlling the language in use.

Buchweitz and colleagues (2012) developed the first study that was able to predict the brain activity associated with the task of thinking about the properties of words of two categories (*dwellings* and *tools*) and two languages in late bilingual Portuguese-English participants (mean AoA: 13). Proficiency was assessed by means of a language background questionnaire that revealed that all the participants had previously taken the TOEFL test. Prior to the fMRI session, participants were asked to list the properties of 14 exemplars of the two categories chosen, although there was no attempt to impose consistency across participants in the choice of properties. During the fMRI session, participants were instructed to read, silently, each word presented individually and think actively in the properties of the presented concept (as in the studies carried out by Mitchell et al. (2008a); Shinkareva et al. (2008, 2011, 2012); & Just et al. (2010)).

The stimuli consisted of seven exemplars of two categories in English and their respective translations into Portuguese (*tools: hammer, screwdriver, saw, wrench, pliers, hatchet* and *drill*; *martelo, chave de fenda, serra, chave de boca, alicate, machadinho,* and *furadeira; dwellings: palace, castle, shack, apartment, mansion, hut,* and *house*; *palácio, castelo, barraco, apartamento, mansão, cabana,* and *casa*) were presented in consecutive blocks of tests, each one in a different order with the items being presented in random order. Each stimulus was presented for 3 seconds, followed by a 7-second resting period in which the participants were instructed to clear their minds and fixate on an X displayed in the center of the screen. Besides, six additional presentations of the fixation for 21 seconds each were implemented, distributed across the session, to provide a baseline measure of activation. The researchers trained machine classifiers to identify the cognitive states associated with the activity of thinking about the properties of each noun in each language, departing from the evoked patterns of functional activity.

As results, Buchweitz and colleagues (2012) demonstrate that semantic processing is organized in the brain over a common network of areas, allowing the reliable decoding of representations across languages in late, proficient bilinguals. Findings suggest that the brain areas involved in decoding semantic content are not affected by stimulus type, be it in English, in Portuguese, in drawing or word format. In the authors' own words, "it is possible to identify which word a person is thinking about based on their representation for the same word in a different language" (Buchweitz et al., 2012, p.289) due to the commonality of representation.

In the same line, Correia and colleagues (2014) extended Buchweitz et al.'s (2012) results by testing 10 Dutch-English bilinguals (no information about AoA was provided in the paper). Proficiency was assessed by means of vocabulary tests. Participants listened to single-words of two categories: *animals* and *objects*. Results corroborate those of Buchweitz and colleagues (2012) and add that "semantic-conceptual knowledge is organized in language-independent form in focal regions of the cortex" in bilinguals (p.336). Such regions are the STG, the medial anterior temporal lobe, the anterior insula in the RH; the anterior temporal lobe (ATL), angular and postcentral gyri in the LH; and the bilateral occipital cortex. In the authors' words, "our observation of language-invariant representations of spoken words in the left ATL concur with the role attributed to this region as a central semantic hub emerged by the integration of distributed sensory and property-based specific representations" (p.337).

More than half of the studies reviewed here indicate that concepts in L1 and L2 are represented in the same brain regions. AoA does not seem to play such an important role as previously considered in the literature. In turn, researchers suggest that proficiency level plays a larger role in how the bilingual brain processes words. The studies reviewed here investigated a variety of pairs of languages: English-Spanish (1 study), Spanish-English (4 studies), Russian-English (1), Japanese-English (1), German-English (1), Chinese-English (1), Portuguese-English (1), Dutch-English (1), and French-German (1). As a general finding, processing of single words recruits the reading classical language areas, but there seems to be language-specific differences due to orthographic transparency. Some studies reported total overlap of activation for L1 and L2 processing, allowing researchers to train classifiers to decode representations across languages. Alternatively, a good number of studies have also suggested that L2 processing relies on a more widely distributed set of areas than the processing of the L1. It is paramount to keep in mind that these conclusions were reached through the study of words out of context. Let us turn to the following subsection where I review sentence-level processing studies.

2.3.3 Sentence-level neuroimaging studies

Word recognition rarely occurs out-of-context
(Van Assche et al., 2012, p.3)

According to Van Assche and colleagues (2012), the ecological validity of studies at the word-level may be tested by investigating word recognition in sentences. Usually, people read words inside meaningful sentences, inside a larger piece of discourse. Processing of words in context may differ from the processing of words in isolation. For example, words in a sentence may restrict the lexical activation to words of the target language, a strategy that might speed up word recognition since it reduces potentially the number of lexical candidates. Studies on this level also tackle the effects of AoA and PL on sentence processing. In this context, I present, in this subsection, a review on neuroimaging studies about sentence-level processing in bilinguals.

Chee and colleagues (1999), to my knowledge, were the first to investigate sentence-level processes[24] in reading with fMRI in bilinguals. Their aim was to ascertain whether differences in the surface features of different languages, such as orthography, phonology, and syntax, affect brain organization at the sentence level of processing. Participants were nine early fluent Mandarin-English bilinguals who had

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[24] I acknowledge that there were other studies as the ones conducted by Perani and colleagues (1996, 1998, PET) and Dehaene and colleagues (1997, fMRI) that dealt with discourse level processes (listening to stories) in bilinguals. Kim and colleagues (1997, fMRI) asked bilinguals to produce sentences silently while they were inside the scanner. As the focus of this study is on reading processes, I chose not to review such studies. Appendix A presents tables created to organize and summarize the main findings of the empirical studies cited in this review.

learned the L2 before the age of 6, and they were asked to read silently sentences in their L1 and L2 and answer probe questions to control for comprehension while being scanned. Sentences in each language, besides being compared to fixation, were compared to pseudo-word strings in a foreign script. As findings, reading compared to fixation elicited activation in BA 44, 45, 47 (IFG), BA 9, part of BA8 and 6 (middle PFC and SMA), BA 22, 21, 38 (left temporal region), and BA 7 (superior parietal areas bilaterally) and occipital regions. The study indicated a common set of areas activated for both L1 and L2, supporting the idea that concepts are directly accessed from the L2 in fluent early bilinguals.

Nakada and collaborators (2001) explored the neuroanatomic substrates of L1 reading and the effect of L1 on the neural substrates recruited for L2 reading. Participants were highly literate late bilinguals: 5 English-Japanese and 5 Japanese-English (AoA: after 11). Proficiency was assessed by means of standardized tests. They were instructed to read sentences in L1 and L2 while in the fMRI scanner and answer probe questions after the scanning session. As results, the researchers found that Japanese L1 reading patterns were substantially different from those of English L1 reading. There was an activation overlap in left frontal areas, but greater activation in inferior temporal regions for Japanese and bilateral lingual gyrus for English. L2 reading in both groups showed identical activation to L1 reading, suggesting that the L1 impacts the L2. Such results support the hypothesis that "the second language represents the cognitive extension of the first language" (Nakada et al., 2001, p.351), known as the *carryover* hypothesis (Vaid & Hull, 2002).

Wartenburger and colleagues (2003) were interested in clarifying which factors, AoA and proficiency level, influence the cortical representation of grammatical and semantic judgments in L2. To reach such a goal, they recruited three groups of Italian-German bilinguals: 11 early fluent, 12 late fluent, and 9 late low proficient bilinguals. Proficiency was assessed by means of tests applied by the researchers. Participants read 180 short sentences, from which 90 were in each language, and in turn, half were grammatically and semantically correct and the other half contained either grammatical or semantic violations. As results, late low proficient bilinguals exhibited more extensive activations during semantic judgment tasks than late fluent bilinguals in Broca's area and right middle frontal gyrus. The late fluent bilinguals revealed greater activation in left middle frontal and right fusiform compared to the late low proficient bilinguals. For grammatical processing, more activity was found in the left temporo-parietal junction, right lingual gyrus and right inferior parietal lobule for the late fluent bilinguals compared to the late low proficient ones; and no additional activation for the late low proficient group (who behaviorally performed inferiorly) compared to the late high proficient group. The researchers concluded that semantic judgments are mostly dependent on proficiency level whereas AoA largely affects grammatical judgments.

Yokoyama and collaborators (2006) investigated the reading processing of structurally complex (active, passive and implausible) sentences in late bilinguals. Thirty-six Japanese-English bilinguals with moderate fluency, as attested by a proficiency test in the L2, read 72 sentences phrase-by-phrase while in the scanner and had to judge whether they were semantically plausible (*The hunter shot the deer / The deer was shot by the hunter / The deer shot the hunter*). The researchers found an overlap in areas for L1 and L2 processing, but in the L1 (Japanese), passive sentences yielded greater activation than active sentences in the *pars triangularis* of the LH, premotor area and superior parietal regions. They suggest that, "in addition to age of L2 acquisition and L2 proficiency, differences in grammatical construction affect cortical representation during the comprehension of L1 and L2" (p.570).

Buchweitz (2006), in his PhD dissertation, investigated the involvement of WMC in bilingual language comprehension. Twelve proficient Portuguese-English late bilinguals (mean AoA: 13) read and listened to L1 and L2 sentences presented in the rapid serial visual presentation[25] format about general world knowledge and answered comprehension probes while being fMRI scanned. Prior to the fMRI session, they filled out a language background questionnaire and performed the RST (Daneman & Carpenter, 1980). As results, the researcher found comparable L1 and L2 activation, but the L2 yielded additional premotor activation. Reading comprehension recruited more LH areas than listening; particularly in the fusiform gyrus and left inferior occipital lobe, areas traditionally associated with the processing of visual stimuli. As regards WMC, lower capacity readers recruited

[25]The RSVP format is an unconventional form of rapid reading because words appear on the screen one at a time. According to Buchweitz and colleagues (2009a), it "differs from normal reading because the duration of gaze on each word is not under the control of the reader, words cannot be skipped, and the words that have already been read cannot be read again (no backtracking)" (p.113).

significantly more voxels in the RH, which corroborates the spillover of brain activation proposed by Prat, Keller and Just (2007). As well, lower capacity readers displayed greater activation in the PFC, an area consistently associated with executive control. In turn, higher capacity readers presented greater activation in the left angular, precentral and postcentral gyri and the right IFG, areas normally associated with phonological rehearsal of linguistic information. In the author's own words, "rather than resorting to executive control processes, these readers may have been better able to adapt to the task of reading comprehension in transient, serial form" (Buchweitz et al., 2009a, p.122).

Buchweitz and colleagues (2009b) focused on reading comprehension to investigate the brain activation associated with different orthographies in two Japanese writing systems (*hiragana* and *kanji*) and in English as an L2. Nine Japanese-English late bilinguals (mean AoA: 26) with an intermediate level of proficiency, as assessed by self-ratings in a language background questionnaire, read two-clause negative and affirmative sentences and answered comprehension probes while being scanned. Processing of sentences in *Kanji* activated, more than *hiragana*, the RH occipito-temporal lobe, an area typically associated with visuospatial processing. On the other hand, reading in *hiragana* activated more areas associated with phonological processing. Reading in the L2 (English), compared to both Japanese writing systems, yielded more activation in the IFG, medial frontal and angular gyri. The researchers interpreted such additional activation in the L2 as reflecting "increased cognitive demand for phonological processing and verbal working memory" (Buchweitz et al., 2009b, p.141). Therefore, the L2 required more effortful reading comprehension processes associated with phonological rehearsal in intermediate-level bilinguals. This study adds to the literature by showing the differential brain responses to different writing systems in a sample of moderately fluent bilinguals.

The majority of studies reviewed in this subsection revealed that for proficient bilinguals, brain activation overlaps for the processing of both L1 and L2. Proficiency in the language, as suggested in word-level studies, plays a more significant role in brain implementation of language processes than AoA. The issue of orthographic transparency was also tackled. Pairs of languages studied were Japanese-English (3 studies), English-Japanese (1 study), Italian-German (1), Portuguese-English (1), and Mandarin-English (1). In general, it seems that reading sentences elicit activation in Broca's area, in the PFC and SMA as well as the temporal region, superior parietal areas and occipital regions. It seems that a large network of areas, especially in the LH, is involved in reading sentences, and studies are revealing the involvement of RH areas, especially in the processing of L2 in late bilinguals. As the focus of this study is to compare language processing in bilinguals and monolinguals, that is the topic of the following subsection.

2.3.4 Brains of monolinguals and bilinguals compared

A great number of studies about the neural implementation of language processing in bilinguals have compared the brain activity yielded by first versus second language processing, also focusing on variables as AoA and proficiency level. Despite this focus, studies have not been focusing on the direct study of language processing in the brains of bilinguals compared to monolinguals. In this subsection, I review studies that accomplish the feat. Due to the scarcity of studies on the sentence-level, I review two studies involving word-level processing and one about sentence-level processing in the brains of monolinguals and bilinguals.

Kovelman, Baker and Petitto (2008) was, to my knowledge, the first study to compare monolinguals and bilinguals' brains with fMRI. Their aim was to investigate whether a bilingual brain, even when a bilingual is using only one language, processes linguistic information in the same manner as a monolingual brain. The participants, 11 Spanish-English early bilinguals and 10 English monolinguals, read sentences while being fMRI scanned. The monolinguals were considered as such because they had no exposure to other languages until the age of seven, and the bilinguals had their proficiency in the L2 assessed by means of a language background and use questionnaire and a language proficiency test. The monolinguals read 40 sentences in English, and the bilinguals read the same and 40 additional sentences in Spanish. Their task was to read silently and judge the plausibility of the sentences. Results revealed that both monolinguals (English) and bilinguals (Spanish-English) activate the same classical areas of the brain to process language. Nonetheless, bilinguals had increased activation in the left inferior frontal cortex (BA 45) when processing English than the English monolinguals. The researchers propose that this differential activation for bilinguals and monolinguals may indicate that "bilinguals have a *differentiated* neural pattern of activation for each language." (Kovelman et al., 2008, p.14). In addition, the results suggest that the bilingual's two languages may have a functional separation in one brain "*based on* the formal linguistic properties" (p.14) of each language.

Parker Jones and colleagues (2012) recruited a total of 67 participants to explore whether brain activation differs for bilinguals and monolinguals when the bilinguals are tested in a single language context. Such a high number of participants for an fMRI study is divided into 4 groups: a group of 36 monolinguals scanned in English; another group of 10 heterogeneous bilinguals (L1: German, Italian, Dutch or Czech; L2: English); another of 10 Greek-English bilinguals that were only scanned in English; and a group of 11 Greek-English bilinguals that were scanned in both languages. Participants' mean AoA of the L2 was 9 years old. They performed a battery of language and control tests before being fMRI scanned. The study presented a complex design with eight different conditions: four required a speech production response and four required a lexical-semantic decision. For each type of response, there were four types of stimuli: pictures of familiar objects, written object names, pictures of nonobjects, and Greek symbols. In addition, the bilingual participants were scanned in different days to avoid repetition effects. As findings, bilinguals, either naming pictures or reading words aloud in their native or nonnative language, showed more activation in six left-lateralized regions: planum temporale, dorsal precentral, STG, pars opercularis, pars triangularis & insula. Such areas were also sensitive to increased speech production demands in monolinguals. In the authors' own words, "the advantage of being bilingual comes at the expense of increased demands on word retrieval and articulation, even in simple picture naming and reading tasks" (Parker Jones et al., 2012, p.901).

In a very recent study, Palomar-García and collaborators (2015) examined the brain activity of a group of 23 early and high-proficient Spanish-Catalan bilinguals to that of a group of 21 Spanish monolinguals. The novelty in the study is that both groups of participants performed tasks in the fMRI only in their native language (Spanish). Bilinguals were interviewed about their daily use and exposure to both languages in a variety of contexts and were required to answer a questionnaire about their language history. The tasks involved listening to words passively and naming pictures. The results revealed that differences appeared only in the picture-naming task. In such task, the bilingual brain reduces the participation of the left MTG, but recruits areas in the medial parietal region and widely spreads neural activation to the right STG. The authors point out that it is "the first study to show that monolinguals use more posterior language-related brain areas (i.e., left middle temporal gyrus) than bilinguals during a language task like picture naming" (p.41). They conclude that native language processing in the bilingual brain takes place in a large-scale language network that differs a bit to that recruited by monolinguals.

In a nutshell, these three studies, despite the methodological differences, reveal that monolinguals and bilinguals activate the same classical areas of the brain to process language. Nevertheless, bilinguals seem to display more activation in such areas and even may recruit other areas, even when processing their L1.

This chapter sought to present the state of the art, in terms of theory and empirical evidence, about the representation of concepts and the processing of reading in the L1 and in the L2. There is substantial literature about the processes involved in reading in the first language, but less is known about bilingual reading in the brain. Research on bilingualism has tended to focus on word-level studies and variables such as proficiency level and age of acquisition. Controversies apart, scholars seem to agree that both languages are represented in similar brain areas, with the L2 displaying a more distributed set of regions than the L1. Due to the scarcity of studies comparing bilinguals and monolinguals, the present study seeks to investigate the neural response to reading in the L1 and the L2 in bilinguals as well as the neural response to reading in the L1 in monolinguals and bilinguals. In the following chapter, Method, the reader will find the description of the study design, the participants, the materials, and the procedures for data analyses.

CHAPTER 3
METHOD

The method of scientific investigation is nothing but the expression of the necessary mode of working of the human mind. (Thomas H. Huxley, on Our Knowledge of the Causes of the Phenomena of Organic Nature, 1863)

This chapter describes the method used to investigate the processing of reading sentences in monolinguals (Portuguese speakers) and late bilinguals (Portuguese native speakers and speakers of English as a second language). In order to do so, the objectives, the research questions and hypotheses of this study will be outlined, followed by a description of the study design, the participants, the instruments and procedures of data collection and analysis. It is crucial to highlight that the study obtained approval from the *Carnegie Mellon University Institutional Review Board* (IRB protocol HS14-474) and that the procedures for collecting data with human beings were followed as described in the approved document.

3.1 OBJECTIVES

The main objective of the present study is to investigate the monolingual and bilingual brains and their neuroanatomical response to the processing of written sentences. To be more specific, this study aims at investigating:

1. the brain areas recruited to the processing of sentences in each of the languages and whether there is any kind of overlap (shared representation of concepts) in bilinguals; and whether there is any kind of overlap in the processing of the first language in monolinguals and bilinguals;

2. the possibility of using machine learning techniques and multi-voxel pattern analysis to identify the semantic neural representation of sentences in one language based on the brain activation for the same sentences in another language;

3. whether individual differences as proficiency in the second language and working memory capacity modulate brain activation in bilinguals; whether working memory capacity modulates brain activation in monolinguals; and

4. whether word length and lexical frequency have an effect on brain activation of bilinguals and monolinguals.

3.2 RESEARCH QUESTIONS

In order to pursue the aforementioned objectives, the present investigation, cross-sectional, quantitative and exploratory in nature, attempts to answer the following research questions:

RQ1: Are both languages (Portuguese and English) represented and processed in the same areas of the bilingual brain? If so, to what extent?

RQ2: Are the same areas recruited for processing sentences in Portuguese for monolinguals and bilinguals? If so, to what extent?

RQ3: Is it possible to identify the semantic neural representation of sentences in one language based on the brain activation for the same sentences in another language in late bilinguals? How? With what accuracy?

RQ4: Do individual differences, namely proficiency in the second language and working memory capacity, modulate brain activation in bilinguals? Does working memory capacity modulate brain activation in monolinguals?

RQ5: Do word length and lexical frequency have an effect on brain activation of bilinguals and monolinguals?

3.3 HYPOTHESES

Drawing on the research questions and objectives outlined above, a set of hypotheses was formulated. They are based on the view that the language network is more extended than the classical language regions (Broca's and Wernicke's areas), including right hemisphere areas; and that languages in bilinguals recruit overlapping areas for proficient late bilinguals (Illes et al., 1999; Buchweitz et al., 2012). In the case of monolinguals, we follow Palomar-García and collaborators (2015, p.43) in that “native language processing in the bilingual brain is supported by a large-scale network that differs to that recruited by monolinguals”. As found by Kovelman and colleagues (2008) and Parker Jones and colleagues (2012), bilinguals recruit more cortical tissue to process their L1. Palomar-García et al’s fMRI study is the first to compare bilinguals and monolinguals processing their native language in a passive listening task and a picture-naming task. To our knowledge, the present study is the first to compare bilinguals and monolinguals processing visually presented sentences in their native language. Our hypotheses are presented as follows:

Hypothesis 1: The same brain regions will be recruited for the processing of L1 and L2 sentences in bilinguals (Chee et al., 1999; Illes et al., 1999; Isel et al., 2010). Being English a deep orthography language, it is expected to find more visual areas recruited for English than for Portuguese, a shallow orthography language (Buchweitz, 2006, Buchweitz et al., 2012).

Hypothesis 2: Bilinguals will display increased activation compared to monolinguals (Kovelman et al., 2008; Parker Jones et al., 2012; Palomar-García et al., 2015). It is expected that the bilingual brain will spread neural activation to right-lateralized regions, as the right superior temporal gyrus, an area traditionally implicated in lexical-semantic processing.

Hypothesis 3: It will be possible to identify the semantic neural representation of sentences in Portuguese based on the brain activation for the same sentences in English, and vice versa, in late bilinguals. Concrete nouns have been already reliably decoded in bilinguals in Buchweitz and colleagues’ study (2012) and in Correia and colleagues’ (2014) study. The challenge here is to decode words in the context of sentences.

Hypothesis 4: In spite of the small sample size (12 bilinguals and 10 monolinguals), it is expected that proficiency in the second language (for bilinguals) and working memory capacity (for both bilinguals and monolinguals) will modulate activation in specific brain regions. It is expected to find greater semantic processing effects (Wartenburger et al., 2003) as well as spillover of activation in the right hemisphere for increasing demands (Prat et al., 2011).

Hypothesis 5: It is expected that word length and lexical frequency will have an effect on brain activation of monolinguals and bilinguals. Word length effects will be found in visual areas (Just et al., 2010) and lexical frequency effects will reflect the route participants will be using to access the meaning of words (Jobard et al., 2011).

3.4 RESEARCH DESIGN

In order to address the research questions and hypotheses of the present study, table 3.1 presents its design. Such study design was established after a pilot study with one participant (due to the high costs of running an fMRI experiment). We had 12 bilinguals and 10 monolinguals participating in the study. Data collection happened from August 11 to September 11, 2014 with 12 bilinguals and 4 monolinguals. From February 7 to 14, 2015, we collected data with 6 more monolinguals.

Table 3.1. Research Design

<table>
<tr><th colspan="3">Bilingual Participants</th></tr>
<tr><th>1st encounter</th><th>2nd encounter</th><th>3rd encounter</th></tr>
<tr><td>✓ Consent Form
✓ Demographic Questionnaire
✓ Handedness Questionnaire
✓ Instructions
✓ Scan 1 (in one language)
✓ Recognition Task
✓ Debriefing</td><td>✓ Consent Form
✓ Instructions
✓ Scan 2 (in the other language)
✓ Recognition Task
✓ Debriefing</td><td>✓ RST in one language
✓ WM Questionnaire
✓ Language Background Questionnaire
✓ TOEFL
✓ RST in the other language
✓ WM Questionnaire</td></tr>
<tr><th colspan="3">Monolingual Participants</th></tr>
<tr><th>1st encounter</th><th colspan="2">2nd encounter</th></tr>
<tr><td>✓ Consent Form
✓ Demographic Questionnaire
✓ Handedness Questionnaire
✓ Instructions
✓ Scan in Portuguese
✓ Recognition Task
✓ Debriefing</td><td colspan="2">✓ Language Background Questionnaire
✓ RST in Portuguese
✓ WM Questionnaire</td></tr>
</table>

For the bilinguals, the study involved three individual sessions. In the first one, this researcher read the consent form (see Appendix D) in the language the participant was going to be fMRI scanned that day; in fact, the whole session occurred in the language the participant would be scanned (English when s/he would scanned in English; Portuguese when s/he would be scanned in Portuguese). *Carnegie Mellon University Institutional Review Board* approved the consent forms (IRB protocol HS14-474). In sequence, the participant answered the demographic questionnaire (see Appendix E), which is standard practice in CCBI experiments with screening for contraindications for the scanning component of the study, and the handedness questionnaire (Oldfield, 1971; see Appendix F). This researcher gave the task instructions to the participant, explained in details what the participant would be doing inside the scanner and made sure the participant was doubtless about the procedures (see Appendix G). The participant was taken from the behavioral testing room to the fMRI simulator room (SIBR: *Scientific Imaging & Brain Research Center* located in Wean Hall, 3rd floor, Carnegie Mellon University Pittsburgh Campus). In such room, the participant was put into an fMRI simulator to practice the task the participant would perform inside the real scanner. The simulator is a full-scale replica of an MRI scanner which introduces subjects to the environment experienced in the scanner, including the sounds that the scanner will make, while also training subjects to minimize head-motion using a head-tracking device and auditory feedback. This familiarization is thought to reduce the participant's anxiety and increase focus. Subsequently, the participant was taken to the real scanner, the fMRI technologist screened her/him once again to make sure s/he would not have any problems inside the scanner. The participant received earplugs and was adequately positioned inside the scanner. This researcher was present throughout the whole session, talking to the participant via intercom at the end of each of the four blocks. After being fMRI scanned, the participant was taken to the behavioral testing room to perform the recognition task (see Appendix H) on a computer. As soon as s/he finished, the researcher and participant completed the debriefing questionnaire (see Appendix I).

In the second session (scheduled according to the participant's availability), the researcher read the consent form with the participant in the language s/he was going to be scanned that day. The order of scannings was counterbalanced. Six participants were scanned first in Portuguese and 6 in English; the 6 who were scanned in Portuguese first, were scanned in English in the second sessions, and vice-versa.

The second session involved reading the consent form, instructions, fMRI simulator, fMRI scanning, recognition task and debriefing. The third and last session involved 2 WMC tests (Reading Span Test: Daneman & Carpenter, 1980; and Teste de Capacidade de Leitura: Tomitch, 2003 adapted by Bailer, 2011), a retrospective WM questionnaire (see Appendix J), an adapted shortened version of the reading section of the TOEFL test (see Appendix K) and a language background questionnaire (adapted from Buchweitz, 2006, see Appendix L). The order of implementation of the WMC tests was counterbalanced to control for order effects.

For the monolinguals, the study involved two individual sessions. The first session was exactly the same as for the bilinguals in Portuguese. The second session (behavioral tests) included a language background questionnaire (see Appendix L), the RST in Portuguese, and a retrospective WM questionnaire (see Appendix J).

Participants were financially compensated at the end of each session. They received $75 for each fMRI session and $10 for each hour of behavioral tests. This financial compensation happened due to the support provided by the *Office of the Director of National Intelligence* (ODNI), *Intelligence Advanced Research Projects Activity* (IARPA), via *Air Force Research Laboratory* (AFRL) contract number FA8650-13-C-7360. Some weeks after the sessions, the participants received through e-mail a picture of their brain (structural image). This researcher acknowledges the importance of providing feedback to participants. Dörnyei (2003, p.90) states that "[…] surveyors typically exploit their participants without offering anything in return - as soon as the data have been gathered, they disappear". For the author, offering feedback is a nice gesture that prepares the grounds for future surveys. Due to the nature of the study, the task performed inside the scanner, and the analyses implemented, participants did not receive feedback individually. As soon as this PhD dissertation is defended, they will receive an electronic copy of it as well as copies of the articles published in academic journals.

3.5 PARTICIPANTS

Participants were recruited through online social networks and printed posters fixed in *Carnegie Mellon University* and *University of Pittsburgh* walls (see Appendix B). Upon first contact through e-mail, the researcher reinforced the pre-requisites for participation and sent them the fMRI Scan FAQ (see Appendix C) so that potential participants could read and write back to the researcher with their doubts. Only after making sure the potential participant read the document, the researcher scheduled the participant according to the SIBR schedule and the participant's availability.

3.5.1 Bilinguals

Twelve right-handed Brazilian Portuguese-English bilinguals participated in the study (four females and eight males). Mean age at the time of data collection was 27.4 years (*SD* = 3.2; *range* = 20-32 years). They reported normal to corrected-to-normal vision and no history of traumatic head injuries. Degree of handedness varied from 80% right-handed to 100% (*M* = 91.66; *SD* = 6.62). They reported coming from a variety of Brazilian states (*Rio Grande do Sul*, *Santa Catarina*, *Paraná*, *São Paulo*, *Minas Gerais*, *Ceará* and *Pernambuco*).

Mean age of initial English learning (L2) was 12.9 years old (*SD* = 4.7; *range* = 7-22 years), thus they may be considered late bilinguals (Grosjean, 2012). All twelve participants were highly proficient in L2 at the time of data collection. Four of the participants were enrolled in graduate-level courses, and four in undergraduate, at *Carnegie Mellon University*, the *University of Pittsburgh*, or *Point Park University* at the time of data collection. From the four participants who were not students at the time of data collection, two had already concluded the graduate level and two the undergraduate level. Eight of the twelve participants had passed university-level English proficiency exams (TOEFL, IELTS) prior to beginning schooling in the US and the remaining four had their proficiency in English attested by the Brazilian university where they came from. To validate their English proficiency formally, participants were required to perform a shortened and adapted version of the reading section of a TOEFL test available online[26]. Our participants exhibited very good proficiency with a mean of 8.53 (*SD* = 1.16; *range* = 6.7-10.0, maximum possible score: 10). They were also asked for self-ratings on the four skills (reading, listening, speaking and writing) on a scale of 1.0 (poor) to 5.0 (excellent) in a language background questionnaire (adapted from Buchweitz, 2006). Overall, the participants

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[26]The TOEFL test is produced by Educational Testing Service©. For the purposes of the present study, this researcher shortened and adapted the reading section of the sample questions available at <https://www.ets.org/Media/Tests/TOEFL/pdf/SampleQuestions.pdf>. For the proficiency test applied in the present study, see Appendix K.

rated themselves as being highly proficient in reading (*M* = 4.75; *SD* = 0.45; *range* = 4.0-5.0), listening (*M* = 4.75; *SD* = 0.45; *range* = 4.0-5.0), writing (*M* = 4.5; *SD* = 0.67; *range* = 3.0-5.0), and speaking (*M* = 4.08; *SD* = 0.79; *range* = 3.0-5.0). At the time of data collection, participants had been living in the United States for a mean of 2.02 years (*SD* = 2.35; *range* = 0.5-9 years) and three of them had already lived in an English speaking country before (*M* = 0.20; *SD* = 0.57; *range* = 0.16-2 years). All participants reported spending most of their day using English (from 6 to 10 hours). From this period, 6 participants reported spending more than 4 hours reading; 1 participant, from 2 to 4 hours; 3 participants, from 1 to 2 hours; and 2 participants reported reading less than an hour a day. As regards the material they read, all participants reported reading online material; nine, books; eight, academic materials; eight, magazines; four, newspapers; and one, work-related material. Though participants rated themselves as being highly proficient in the L2, it is likely that some if not most of the bilinguals in the study are unbalanced bilinguals (i.e. proficiency in L1 is superior to L2, or vice versa).

All participants reported spending some time of their day using Portuguese. One participant informed spending about 6 hours; 5 participants informed 4 hours; 3 participants, from 2-3 hours; 2 participants, from 1-2 hours and 1 participant, less than an hour. From this period, one participant reported spending from 2 to 4 hours reading in Portuguese; 5 participants reported spending 1 to 2 hours; and 6 participants, less than an hour a day. As regards the material they read in Portuguese, all participants reported reading material online; eight reported reading books; two, academic material; and one, newspapers and magazines in Portuguese. In addition, eight participants reported having a very low degree of proficiency in a third language. From the eight, six reported knowing something in Spanish, one in French and one in Italian.

3.5.2 Monolinguals

Ten right-handed Brazilian Portuguese monolinguals participated in the study (four males and six females). Mean age was 28.6 years (*SD* =4.4; *range* = 21-38 years) at the time of data collection. Participants reported normal to corrected-to-normal vision and no history of traumatic head injuries. Degree of handedness varied from 66% right-handed to 100% (*M* = 88.97; *SD* = 11.93). They reported coming from a variety of Brazilian states (*Santa Catarina*, *Paraná*, *São Paulo*, *Espírito Santo, Piauí, Ceará* and *Pernambuco*).

Participants reported not speaking any second language; though some of them (8) had contact with English, Spanish or French in regular school or in private language institutes, they stated not knowing how to communicate in a second language. Just one participant from the sample had already lived abroad (a month in San Diego, California to accompany her husband). Four participants from the sample were in Pittsburgh at the time of data collection visiting friends or a family member for a few days. The remaining six participants were in Pittsburgh to start learning English: four were in the city for a month or less and two were living there for about two years. It is important to highlight that this couple (the one that was living in the US for two years) ensured not to communicate in English. They lived with a Brazilian family member who lived in Pittsburgh for about 10 years; they worked for a cleaning company with other immigrants from Latin America and reported not needing English for survival, though they acknowledge planning to learn English in the future because their kids are attending school in the US. Actually, all the ten participants reported having interest in learning English in the future for tourism and professional reasons.

As regards schooling, four participants had taken graduate courses and specializations in Brazil; three had completed undergraduate courses; one participant, technical course; and two, high school. Compared to the bilingual sample, the monolinguals display a little lower level of formal education.

3.6 EXPERIMENTAL PARADIGM

Participants read 60 sentences in English and their translations to Portuguese (e.g. The diplomat negotiated at the embassy/*O diplomata negociou na embaixada*) while fMRI scans were acquired in two separate days. As abovementioned, the language of presentation was counterbalanced: half of the participants were fMRI scanned first in English and half in Portuguese.

The English sentences were a portion of the stimuli from a larger study with native speakers of English (Wang, Cherkassky & Just, 2016) and were translated to Portuguese by a native Portuguese speaker. As regards the translation process, this researcher translated them from English to Portuguese, sent the Portuguese translations to two PhD colleagues (native speakers of Portuguese and highly fluent in English) from the same program (Language Studies) at UFSC to translate them to English. Then, I showed the colleagues/translators the original sentences in English, asked them to suggest modifications to the Portuguese translations. As a final step, I sent the agreed Portuguese sentences to a scholar from PPGI, who considered the sentences in Portuguese and in English as equivalents in meaning. The sentences obey the SVO (subject-verb-object) order and have a mean length of 3.23 content words. The verbs are all in the simple past tense and the majority of sentences have an adjective as a modifier of the subject or the object, or both (e.g. *O paciente cansado dormiu no hospital escuro*/The tired patient slept in the dark hospital) (see Appendix E for the complete list of sentences). Word length in Portuguese ranged from 3 to 11 letters (e.g.: *rua*, *restaurante*), with a mean of 6.79 (*SD*=2.00), while English word length ranged from 3 to 10 letters (e.g.: *car*, *television*), with a mean of 5.66 (*SD*=1.70). Lexical frequency in English was assessed through the CELEX database and frequency in Portuguese, through *Corpus do Português*[27], taking into consideration the frequencies for Brazilian Portuguese.

The sentences were presented in white against a black background. Each sentence was divided into several phrases (e.g. The family, was, happy/ *A família, estava, feliz*). Each phrase was presented one at a time, left justified, in a moving window format. Participants were instructed to read silently each phrase as they appeared on the screen and to think about the meaning, the properties they associated with the words in that phrase. The presentation of each sentence and blank interval - in which participants were instructed to think about the meaning of the whole sentence - lasted five seconds. After each blank interval, an X appeared on the center of the screen for seven seconds and participants were instructed to fixate and clear their minds. Each fMRI session lasted about one hour and there were four scans in total (53:28min). Each scan presented the full set of 60 sentences, divided into three blocks of 20 sentences, with the order randomized. There were 16 additional presentations of a fixation, 17 seconds each, distributed across the session, to provide a baseline measure of activation. As each stimulus is presented trial-by-trial sentence-fixation-sentence), we can say that we have an event-related design. According to Bookheimer (2002), an event-related design "presents one stimulus at a time, allowing the blood flow response to rise and fall for that particular item before presenting a second stimulus" (p.154). The control condition was rest. A schematic representation of the paradigm is shown in figure 3.1 next page:

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[27]Available at <http://www.corpusdoportugues.org/>.

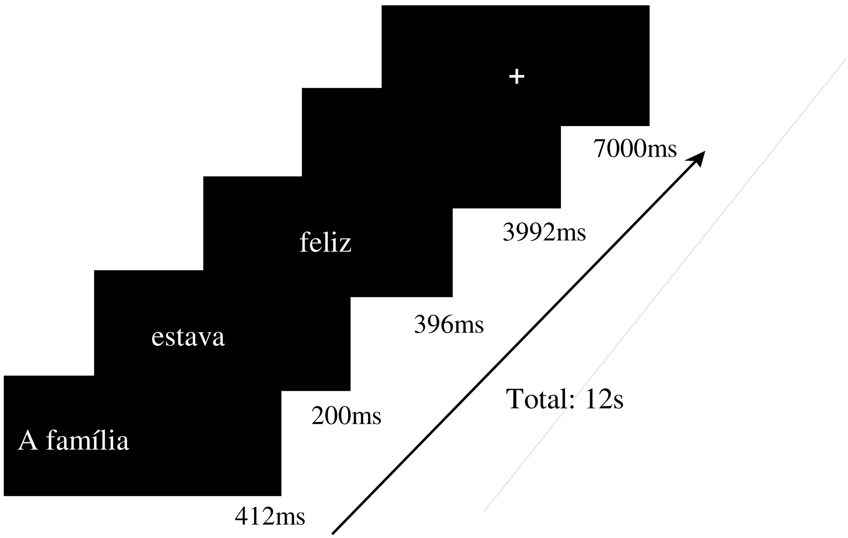

Figure 3.1. Schematic representation of the experimental paradigm. The duration of each phrase was determined by a regression model based on a reading speed pilot (Formula: 300 milliseconds x number of words + 16 milliseconds x number of characters, in which the number of words is the sum of content words and *was*, and the number of characters includes all words except *the*).

After each fMRI session, participants were required to perform a recognition test to ensure they paid total attention to the sentences while in the scanner. The test in each language comprised 60 sentences (half present in the fMRI task, half new sentences). Results indicate that bilingual participants could actively process the sentences, because they could distinguish seen from unseen sentences with a mean accuracy of 97% (*M* = 58.25; *SD* = 1.91; *range* = 54-60) in English and 97.2% (*M* = 58.33; *SD* = 1.49; *range* = 56-60) in Portuguese. As regards monolinguals, they distinguished seen from unseen sentences in Portuguese with a mean accuracy of 93.3% (*M* = 56; *SD* = 3.65; *range* = 48-60). Comparing performance, the bilinguals could recognize seen sentences with a higher mean accuracy than monolinguals.

In relation to the debriefing, participants reported feeling moderately comfortable inside the scanner (just one participant reported feeling uncomfortable in the first scan). The main complaints were the noise and the fact of having to remain motionless during almost one hour. As regards the specific way each participant thought of the sentences, all of them reported creating a very vivid mental image with images, sounds, situations. One participant actually reported "picturing" the sentence. With regard to the timing of presentation of the phrases, three participants reported it being ok, while the remaining nineteen considered it too fast; they indicated that it was too fast to think of each phrase separately, but they could think of some words while they were appearing on the screen and integrate in the blank screen before the fixation. Four participants reported that the meaning of each sentence came only at the end, whereas eighteen participants reported it coming both while each phrase was presented and at the end.

Participants also performed two working memory capacity tests, the RST (adapted from Daneman & Carpenter, 1980) and its Portuguese version *Teste de Capacidade de Leitura* (Tomitch, 2003; Bailer, 2011), whose order was counterbalanced to avoid test effects. Bilinguals had a mean of 3.08 (SD = 0.92; *range* = 2-5.5) in Portuguese and a mean of 3.25 (SD = 1.03; *range* = 2-5.5) in English. As expected, scores on both tests have a strong significant correlation ($r = .879$, $p = .000$). It was hypothesized that working memory capacity would not differ between languages within participants, and a paired samples t test was conducted, failing to reveal a statistically reliable difference between the scores on the two tests, $t(11) = 1.173$, $p = .266$, $\alpha = .05$. Monolinguals had a mean working memory span of 2.6 (SD = .45; *range* = 2-3.5). As regards the participants perception of the WMC tests, ten participants reported feeling challenged; five participants reported feeling challenged and exhausted at the same time; four participants, both challenged and comfortable; and three participants, both challenged and anxious. The participants also described the strategies employed to remember the words from the test: (a) as repeating the word mentally (seven participants); (b) trying to relate the meaning of the word to the meaning of the sentence (five participants); (c) creating a mental image of the word (four participants); (d) trying to relate the last words in a meaningful way (three participants); (e) trying to relate the words and creating a mental image (one participant); (f) memorizing the first letter of each word in the order they appeared (one participant); and (g) associating the words and repeating them mentally (one participant).

3.7 FMRI PROCEDURE

Functional images were acquired on a Siemens Verio 3.0T scanner at the *Scientific Imaging & Brain Research Center* (SIBR) of *Carnegie Mellon University* (gradient echo EPI pulse sequence; TR =

1000 ms, TE = 30 ms, and a 60º flip angle[28]). According to the CCBI website, the fMRI machine has a 32-channel coil that produces excellent fMRI and diffusion results. It has a larger bore (70 cm) that provides "substantially more psychological and physical comfort, particularly for children, larger participants, and participants with anxiety"[29].

Sixteen 5-mm thick oblique-axial slices were imaged (1-mm gap between slices). The acquisition matrix was 64 x 64 with 3.125 x 3.125 x 6 mm voxels. According to the CCBI website, "the high imaging speed allows us to obtain many observations of the activation level of each voxel in each experimental condition, and to obtain whole-brain scans, so we can have high-resolution imaging of a large volume of brain"[28].

CogLab is the experimental control system used in CCBI. It synchronizes the acquisition of MR images with the presentation of visual stimuli. A color high-resolution LCD projector projects visual stimuli onto a rear-projection screen in the bore of the magnet. Participants view this screen through an angled mirror system. CogLab attains "near-millisecond accuracy", it "provides a robust platform for running experiments on the nature of cognition"[28].

3.8 FMRI DATA PROCESSING AND ANALYSIS

Data collected at the scanning sessions in Wean Hall were brought to the CCBI lab (Baker Hall) via FTP (File Transfer Protocol) and were placed on the Linux cluster available at the lab. Data were analyzed in several stages using SPM8 (Wellcome Trust Centre for Neuroimaging, University College London). The software contains tools for individual subject processing in addition to options for group analyses. In the first stage of analysis, the signal processing procedures aim at removing several kinds of variation over the course of the session in the MR signal that are unrelated to the experiment. Images are corrected for both slice timing acquisition and participant head motion.

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[28]EPI stands for echo planar imaging, which is "a technique that allows collection of an entire two-dimensional image by changing spatial gradients rapidly following a single electromagnetic pulse from a transmitter coil" (Huettel et al., 2009, p.19). TR stands for repetition time, which is "the time interval between successive excitation pulses, usually expressed in seconds" (Huettel et al., 2009, p.527). TE stands for echo time, which is "the time interval between an excitation pulse and data acquisition, usually expressed in milliseconds" (Huettel et al., 2009, p.520).

[29]CCBI website <http://ccbi.cmu.edu/facilities.html>.

Images are normalized to the Montreal Neurological Institute (MNI) template, resampled to 2 x 2 x 2-mm voxels for specific kinds of analyses, and smoothed[30] with a Gaussian kernel to decrease spatial noise, depending on the analysis employed. At such point, the brain activity is compared among experimental conditions, and in some cases, across population groups. According to the CCBI website, "SPM uses a temporal convolution of the paradigm with a model of the hemodynamic response function of the fMRI signal in a general linear model that estimates parameters of the experimental and confounding effects of the experiment".

To compare the distribution of activation, the images collected with our participants were corrected for slice acquisition timing and for motion, normalized to the Montreal Neurological Institute (MNI) template, resampled to 2 x 2 x 2-mm voxels, and smoothed with a 12-mm Gaussian kernel to decrease spatial noise by making the spatial distribution normal. Statistical analyses were performed on the whole brain at the sentence-level on individual and group data by using the general linear model[31] (GLM). Group analyses were performed using a random-effects model[32]. Statistical maps were superimposed on a T1-weighted anatomical image (template). Automated anatomical labeling (AAL) (Tzourio-Mazoyer et al., 2002), as implemented in the SPM8 software, was employed to name activation cluster centroids and adjacent areas of activation.

For bilinguals, the conditions reading in Portuguese and reading in English were contrasted with fixation, that is, when an "X" was displayed on the center of the screen and participants were instructed to clear their minds. The contrast between English and Portuguese reading

[30]Spatial smoothing entails blurring the "fMRI data across adjacent voxels to improve the validity of statistical testing and maximize functional signal-to-noise-ratio, at a cost of spatial resolution (Huettel et al., 2009, p.220).

[31]GLM is "a class of statistical test that assume that the experimental data are composed of the linear combination of different model factors, along with uncorrelated noise" (Huettel et al., 2003, p.337).

[32]"In random-effect analyses, the appropriate error variance is based on the activation from subject to subject where the effect *per se* constitutes an independent observation and the degrees of freedom fall dramatically to the number of subjects. The term 'random effects' "indicates that we have accommodated the randomness of different responses from subject to subject" (Friston, Ashburner, Kiebel, Nichols & Penny, 2007, p.29). It allows the researcher to generalize to the population from which the subjects were selected.

was carried out based on condition subtraction. The contrast reading in Portuguese and fixation was also carried out for bilinguals and monolinguals reading in Portuguese.

To analyze the difference in representation location for each language across subjects, we computed stability maps at the word-level with voxels 3 x 3 x 6 mm. A Gaussian smooth kernel (12 x 12 x 6 mm) was used to adjust for individual differences in brain anatomy. Hit maps with the most 700 stable voxels were generated across all participants. It is believed that these 700 stable voxels, those that display a consistent tuning curve (Mason & Just, 2015), are consistently selective to the processing of words in the context of sentences in each language.

To analyze whether proficiency in the second language and working memory capacity correlate with brain activation in bilinguals and whether working memory capacity correlates with brain activation in monolinguals, contrast files were generated by reading-fixation in each language for each subject (within-subject design) and the second level model (between-subject design) was built upon these contrast images by paired *t* test. Word length and lexical frequency effects were correlated with the difference between languages to check whether they might modulate language difference.

We also implemented multi-voxel pattern analysis (MVPA) and machine learning[33] techniques to identify the semantic neural representation of sentences in one language based on the brain activation for the same sentences in another language. Instead of focusing on single voxels, MVPA uses pattern-classification[34] algorithms to multiple voxels to decode the pattern of activity.

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[33]Machine learning is defined as "a subdiscipline within computer science that develops algorithmic rules for relating input data to desirable outputs" (Huettel, Song & McCarthy, 2014, *website*).

[34]Pattern classification is "an attempt to separate individual examplars into different categories by constructing a set of decision rules based on some combination of their features" (Huettel et al., 2014, *website*). According to Lindquist (2014, personal communication), MVPA steps include (1) feature selection: identifying a subset of voxels within a pre-determined region(s) of interest and identifying the BOLD amplitude in each voxel at each of the time points; (2) training and testing sets: researchers partition their data into a training set (a classifier has a number of parameters that needs to be estimated or learned; such learning is performed on a subset of the observations, the training set) and a testing set (once trained, the classifier is evaluated using an independent set of observations – if it truly captures the relationship between features and classes, it should be able to predict the class label for data it has not

To reach such a goal, the percent signal change (PSC) was computed at each voxel in the brain image, relative to a baseline activation level measured during fixations for each presentation of a sentence. The signals of the sentence presentation consisted of the mean of five brain images, collected from 7 seconds to 12 seconds post stimulus onset. This temporal window was determined by a preliminary investigation conducted at CCBI, which found that the most decodable neural signatures of all the content words in a simple sentence presented at normal reading speed occurred after the entire sentence had been read. The PSC was then normalized to mean of 0 and variance of 1 across sentences within each block of presentation to equate the overall intensities across scans. Because each sentence in each language was presented four times, four mean PSC images of each sentence of each language could be obtained. Four word images were then obtained by averaging all the sentence images containing the particular word in each respective presentation.

3.8.1 Semantic features

Based on the literature, we created at *Center for Cognitive Brain Imaging* (CCBI), a set of 42 semantic features to aid in data analysis. Each feature intended to characterize a fundamental semantic property and also correspond to a known or plausible neural processing mechanism from previous studies (Just et al., 2010). We call this set the CCBI Features, which were written in binary scale, with 1 indicating the coded word associated with the certain feature, and 0 indicating no association. The final set of CCBI Binary Features is presented in table 3.2. It contains a total of 42 features. The coding was performed by several people with linguistic training. Examples of semantic features include *human group*, *entity of nature*, *perceptual salience*, among others. Six case role features (*subject*, *verb*, *object*, *modifier*, *adjunct*, and *predicate of copular sentence*) were also used. For instance, in the sentence “The family was happy/*A família estava feliz*", we have “the family” as the *subject* and “happy” as the *predicate of copular sentence*. Note that the verb “was” did not receive any code. “Family” was also

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seen before); (3) cross-validation: researchers evaluate whether the pattern classifier can be generalized to new data. MVPA aims at determining the model parameters that allow for the most accurate prediction of new observations. Accuracy of classification measures the fraction of observations in the test data for which the correct label was predicted.

coded as the following features: *social support, human group,* and *person*. "Happy" was coded as *adjective, emotion, positive valence, abstraction*. We carried out the analysis of difference between languages with our 42 semantic features at the word-level with voxels 3 x 3 x 6 with no smoothing.

Table 3.2. Semantic features associated with the 96 content words presented in the context of sentences in the present study:

Feature category	Feature	Definition	Examples in Portuguese	Examples in English
Part of Speech	Verb	self-explanatory	*gostar, dormir, ir, negociar*	like, sleep, go, negotiate
	Adjective	self-explanatory	*amarelo, escuro, famoso, machucado*	yellow, dark, famous, injured
Domain of Human Activity	Conflict	involving aggression and those who commit it	*chutar, soldado, comandante*	kick, soldier, commander
	Health	related to improving or threatening health	*médico, paciente, hospital, sobreviver*	doctor, patient, hospital, survive
	Eating/ drinking	self-explanatory	*restaurante, café, frango, copo*	restaurant, coffee, chicken, glass
	Communication	transfer of action or information; medium of communication	*ouvir, falar, autor, livro, repórter*	listen, speak, author, book reporter
	Sports	self-explanatory	*jogar/brincar, futebol*	play, soccer
	Technical	related to technology or technical skills	*carro, engenheiro, cientista, médico*	car, engineer, scientist, doctor
	Finance	self-explanatory	*comprar, moeda de dez centavos, banqueiro, rico*	buy, dime, banker, wealthy
	Humanities	self-explanatory	*autor, artista, teatro*	author, artist, theater
	Law	self-explanatory	*julgamento, advogado, júri*	trial, criminal, lawyer, jury
	Political/ governmental event or entity	related to civics, politics, military	*protesto, prefeito, político, embaixada*	protest, mayor, politician, embassy

	Knowledge	knowledge or expertise	*engenheiro, escola, livro*	engineer, school, book
Perceptual Characteristics	Man-made	objects made by humans; opposite of "natural"	*mesa, moeda de dez centavos, revista, escritório*	desk, dime, magazine, office
	Natural	(1) occurring in nature; opposite of "man-made;" (2) activities occurring in a natural environment	*flor, tempestade, cachorro, campo*	flower, storm, dog, field
	Inanimate	objects; non-agents	*café, mesa, revista, televisão*	coffee, desk, magazine, television
	Appearance	visual appearance	*amarelo, vazio, noite, escuro*	yellow, empty, night, dark
	Size	size is a salient feature	*passarinho, criança, multidão*	small bird, child, mob
	Color	self-explanatory	*verde, amarelo*	green, yellow
	Positive valence	self-explanatory	*famoso, pacífico/tranquilo, rico, gostar*	famous, peaceful wealthy, like
	Negative valence	self-explanatory	*temer, quebrar, perigoso, tempestade*	fear, break, dangerous, storm
	High intensity	high intensity human or physical state or activity	*gritar, protesto, multidão, perigoso*	shout, protest, mob, dangerous
Animate Beings	Person	self-explanatory	*garota, médico, prefeito, eleitor*	girl, doctor, mayor, voter
	Animal	self-explanatory	*pássaro, cachorro, pato, cavalo*	bird, dog, duck, horse
	Human-group	groups of two or more humans	*casal, família, multidão, futebol*	couple, family, mob, soccer
Time/ Space	Setting	self-explanatory	*parque, escritório, escola, noite*	park, office, school, night
	Unenclosed	An environment without shelter or enclosure	*praia, campo, rua, noite*	beach, field, street, night
	Location saliency	place is a salient feature	*visitar, rua, mesa*	visit, street, desk
	Shelter	enclosures	*carro, escola, hospital, embaixada*	car, school, hospital, embassy
	Change of location	self-explanatory	*carro, turista, atravessar, ir, deixar/sair*	car, tourist, cross, go, leave
	Event	self-explanatory	*protesto, julgamento, futebol, tempestade*	protest, trial, soccer, storm

	Time of event	related to a time period or timing	*noite*	night
Mental action or state	Mental act	requiring cognitive processes; occurring internally	*gostar, temer, encontrar, negociar*	like, fear, find, negotiate
	Perceptual event	self-explanatory	*ouvir, ver, assistir/observar, testemunha*	listen, see, watch, witness
	Emotion	self-explanatory	*temer, gostar, feliz, pacífico/tranquilo*	fear, like, happy, peaceful
	Transfer of possession	related to changing ownership	*dar, comprar*	give, buy
Social action or state	Social interaction	interaction between two or more subjects	*negociar, jogar/brincar, falar, famoso*	negotiate, play, speak, famous
	Social support	relating to a network of social support	*família, pais, casal*	family, parents, couple
Physical action or state	Physical action	an action that has a physical component	*quebrar, chutar, jogar/brincar, andar/caminhar/ entrar/atravessar*	break, kick, play, walk
	Change of physical state	self-explanatory	*quebrar*	break
	Impact	two subjects or objects coming in contact with each other	*quebrar, derrubar, chutar*	break, drop, kick
Abstraction	Abstraction	not physically defined; opposite of concreteness	*comprar, sobreviver, vazio, cansado*	buy, survive, empty, tired

We anticipate a bulk of brain areas to be activated while participants read the sentences on the screen. Following the literature, "words forms are brain-based on specific action-perception circuits distributed over inferior-frontal and superior-temporal areas of cortex" (Pulvermüller, 2012, p.431). Rizzolatti and Craighero (2004) explain that when we observe an action being performed by someone, our brains are comparably activated in premotor mirror neurons as when we are executing the action. So one can hypothesize that when people are thinking of actions like *The family played at the beach*, their brain may elicit similar activity to the one elicited when they are performing the action/having such an experience.

3.8.2 Neurosemantic cuboids

For the semantic neural representation identification, voxels were extracted from 39 pre-determined meta-language cuboids used by Wang et al. (2016). These cuboids emerged from semantic factor analyses of fMRI data from a separate sample of three English monolingual subjects reading 240 sentences composed of 242 content words. Because the 60 sentences in this study are part of this large set of 240 sentences, and the use of cuboids improved substantially the classification results in Wang and colleagues' study, we chose to use them in our analysis. Therefore, we hypothesize that the semantic information of our stimulus set were encoded within these cuboids. Together, they have a mean volume of 7 cm^3 and together comprise approximately 16% of the cerebrum volume. Figure 3.2 depicts the location and sizes of the cuboids. These cuboids were hypothesized to encode meta-language semantic features, such as the 42 CCBI features.

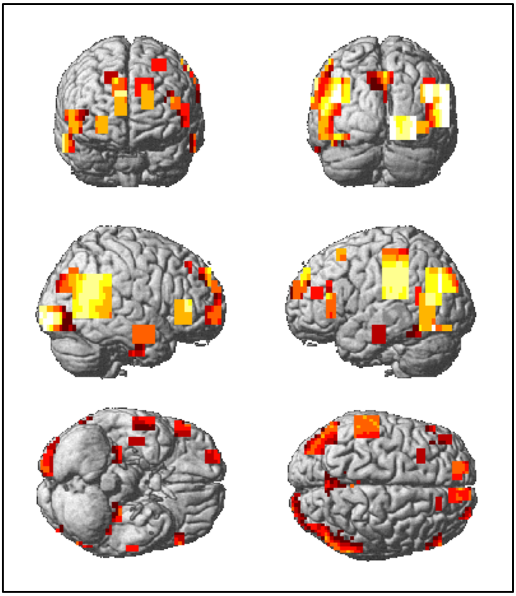

Figure 3.2. Locations of the cuboids.

3.8.3 Neural feature extraction

Cross-language decoding was achieved by first postulating *semantic features* common to all languages, and second, by finding common activation locations (neural features) such that a mapping between the common semantic features and neural features is established. Figure 3.3 describes this procedure. Extracted neural features from the meta-language cuboids were modeled on the meta-language semantic features, such that a direct relationship between them could be established. This relationship is the foundation of the cross-language classification.

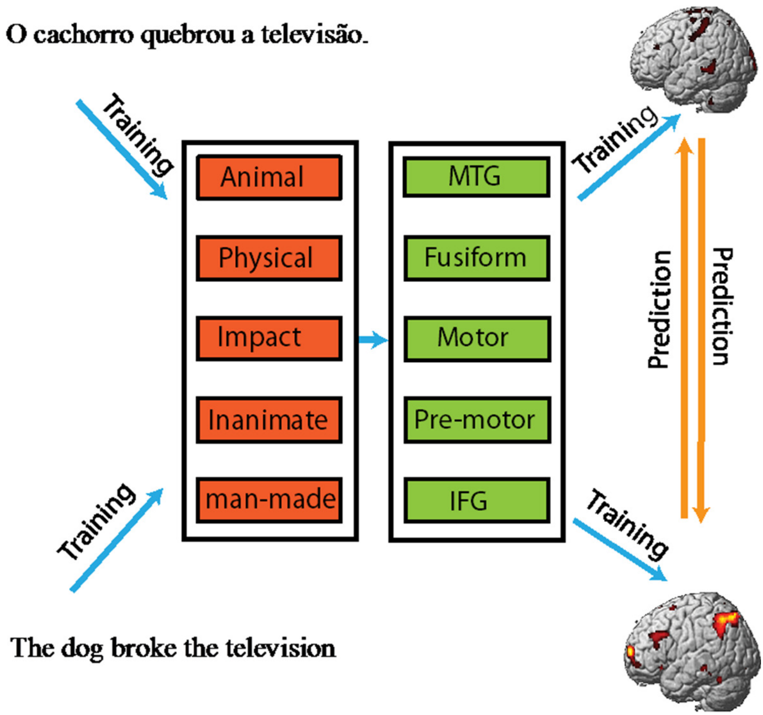

Figure 3.3. The general scheme of cross-language decoding. For the corresponding concepts in different languages, for instance, 'The dog' in English and '*O cachorro*' in Portuguese, 42 common semantic features were coded. These common semantic features were modeled on common neural features.

A classifier was trained to map between the fMRI images obtained when participants read sentences in one language, and applied to decode the translation equivalent sentences in the other language from their fMRI signature. Within each classification fold, common neural features (between the two languages) were selected based on five methods: canonical correlation analysis (CCA) and four other methods based on voxel stability. To equalize the comparison, all the methods extract 290 features for each classification fold.

3.8.4 CCA: Canonical Correlation Analysis

Canonical correlation analysis (CCA) was used to incorporate the semantic-neural mappings in the two languages. CCA produces a linear combination of voxels that is a projection of the relevant voxels in each language, so as to maximize model fit (Rustandi, Just & Mitchell, 2009; Weenink, 2003). Figure 3.4 illustrates this procedure in the two dimensional space. The two black parallelograms indicate the two-dataset spaces. The red and green arrows indicate the voxel values in each space by vectors. The blue arrows are projections that are linear combinations of red or green arrows which could be projected on the other space. Pairs of blue arrows could be found such that the angle between them (ϕ) is the smallest. Because the cosine of this angle is numerically the correlation between the two projections, we are essentially looking for maximally correlated linear combinations of voxels between the two datasets. Therefore, the voxels were transformed into the component space that maximized the commonalities between the training set of English and Portuguese.

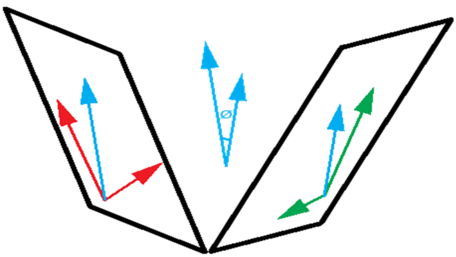

Figure 3.4. Illustration of the CCA procedure. Black parallelograms: representation of the two datasets; Red arrows: voxel values represented as vectors in the first dataset; Green arrows: voxel values represented as vectors in the second dataset; Blue arrows: components found in each dataset, as linear combinations of the vectors, such that the angle between a pair of components is minimized.

3.8.5 Stability-based methods

Because each sentence in each language was presented four times, four mean percent signal change (MPSC) images of each sentence of each language could be obtained. Four word images were then obtained by averaging all the sentence images containing the particular word in each respective presentation. Stability is defined as the pairwise correlations of word images across presentations. There are four direct ways of computing stabilities for the purpose of common neural features extraction: (a) overall stability; (b) cross-language stability; (c) separate stability; and (d) within-language stability of the training language. For all these four methods, only word images in the training set were used, as in the CCA method. Therefore, the neural feature extraction is not contaminated by the test set in any sense.

The (a) overall stability method computed the MPSC signal correlation across all the eight presentations of both the training and testing languages. The most stable voxels were selected as common neural features. The (b) cross-language stability method paired only presentations from different languages, and computed MPSC signal correlation. The most 'bilingual stable' voxels were selected as common neural features. The (c) separate stability method paired presentations within each language and selected the most stable voxels in each language, and then the two sets of voxels were combined as common neural features. Finally, the (d) within-language stability of the training language is similar to the separate stability method, except for the fact that the testing language was not involved in the voxel selection procedure. The most stable voxels were selected based only on the stability of the training set of the training language.

3.8.6 Generative model prediction

The word images in the CCA space, or voxels selected from stability-based methods were used to train a ridge regression model to generate the predicted word images. We added up the predicted word images in the component space or selected voxel space linearly to generate the predicted sentence image. We applied the CCA weights of the test set to obtain the test sentence image in component space. The test sentence image from stability-based methods was the actual sentence image. Then, this image was compared with all the predicted images to yield the rank accuracy of the prediction.

3.8.7 GNB classifiers

In machine learning, naïve Bayes classifiers or Gaussian naïve Bayes (GNB) are a family of simple probabilistic classifiers with strong independence assumptions between the features. According to Mitchell et al. (2004), it "uses the training data to estimate the probability distribution over fMRI observations, conditioned on the subjects' cognitive state" (p.150). In the words of Buchweitz and colleagues (2012), it is a "generative classifier that models the joint distribution of a class Y (categories, e.g.) and attributes (voxels), and assumes the attributes X_1, X_2, X_3, … X_n are conditionally independent given Y" (Buchweitz et al., 2012, p.284). There are a lot of different classifiers, but GNB is "a useful classifier for procedures that need to be repeated many times, such as permutation tests, due to being much faster to train than the others" (Pereira, Mitchell & Botvinicka, 2009, p.7). As it will be seen in the results section, the CCA analysis outperformed the GNB classifier, but it is worth presenting the comparison of accuracy.

The following chapter presents the results of the data analysis. It is important to state that all statistical analyses were performed by the team at CCBI, in special by Ying Yang with the aid of Jing Wang and Vladimir Cherkassky. As stated by Amaro Jr. and Barker (2006), "an fMRI experiment depends upon techniques and methodologies derived from different fields of expertise, making it intrinsically multidisciplinary" (p.220). I would like to thank these fellows for contributing so much to the development of this study.

CHAPTER 4
RESULTS

I dwell in possibility
(Emily Dickinson)

This chapter reports the results of all the statistical analyses conducted to address the hypotheses and research questions of the present study. The chapter is organized into three broad sections: (1) sentence-level analysis, (2) word-level analysis, and (3) semantic neural representation identification. The first section, sentence-level analysis, is divided into four subsections: language difference in bilinguals; differences in processing L1 in bilinguals and monolinguals; L2 proficiency and WMC: effects on language processing in bilinguals; and WMC: effects on language processing in monolinguals. Such section reports the GLM analyses conducted at the sentence level. The second section, word-level analysis, is subdivided into five topics: stability analysis: language difference in bilinguals; stability analysis: differences in processing L1 in bilinguals and monolinguals; word length and lexical frequency effects in bilinguals; word length and lexical frequency effects in monolinguals; and semantic features and differences in the two languages. The third section presents the results concerning the identification of the semantic neural representation of words in the bilingual and monolingual brain. Two types of analyses were conducted: within-language and cross-language classification. In the former, the same language is used to train and test data. In the latter, for instance, data collected in the Portuguese scan is used to train the classifier and data collected in the English scan is used to test the classifier. In all the sections, the results are presented in the form of illustrations (figures, brain renderings and graphs) and tables.

4.1 SENTENCE-LEVEL ANALYSIS

The results reported in the present section come from statistical analyses conducted on the whole brain at the sentence-level on individual and group data by using the general linear model (GLM) as implemented in SPM8. To determine which clusters of voxels were active in each condition and to deal with the problem of multiple comparisons, cluster-extent based thresholding was implemented (Friston, Worsley, Frackowiak, Mazziotta & Evans, 1994). Such an approach detects statistically significant groups of voxels based on the number of adjacent voxels "whose voxel-wise statistic values lie above a pre-determined primary threshold" (Woo, Krishnan & Wager, 2014, p.412). This method controls the estimated false positive probability of the cluster in its entirety, instead of estimating the false positive probability of each voxel in the cluster. It consists of two stages:

> first, an arbitrary voxel-level *primary threshold* defines clusters by retaining groups of suprathreshold voxels. Second, a cluster-level *extent threshold*, measured in units of contiguous voxels (*k*), is determined based on the estimated distribution of cluster sizes under the null hypothesis of no activation in any voxel in that cluster. (Woo, Krishnan & Wager, 2014, p.412)

Cluster-extent based thresholding was implemented due to its relatively higher sensitivity in identifying significant areas as compared to voxel-level correction methods for multiple comparisons (Friston et al., 1994; Woo et al., 2014). However, as all methods, it has limitations. When clusters are too large, there is low spatial specificity: the cluster-level *p*, instead of determining the statistical significance of activation at a specific voxel or area within the cluster, specifies the probability of picking up a cluster of a given size or greater under the null hypothesis. Thus, it is possible to infer that "there is true signal "somewhere" in this huge cluster and cannot make an inference about specific anatomical regions" (Woo et al., 2014, p.413). Woo and colleagues (2014) explain that, in studies with moderate effect sizes and sample sizes (Cohen's d <.8 and N <50), cluster-extent based thresholding indeed offers increased sensitivity to identify activations with large spatial extent. They recommend "using more stringent cluster-defining primary thresholds to reduce the possibility of obtaining false positive clusters and/or large activation clusters, and to improve the degree of confidence in inferences about specific locations/voxels" (p.418). They prescribe p <.001 as a reasonable default for fMRI studies. More liberal primary thresholds than p <.001 (e.g., p <.05) may give inaccurate family-wise error rate (FWER[35]) correction. In our sample of bilinguals ($N = 12$), we

[35]FWER is the probability of making one or more Type I errors in a family of tests, under the null hypothesis (Lindquist, 2014, personal communication). A Type I error happens when the null hypothesis (no effect) is true, but we mistakenly reject it (false positive) controlled by significance level α. Type II errors happen when the null hypothesis is true, but we fail to reject it (false

get a Cohen's *d*[36] of 2.42, effect size *r* of .77 when using a *p* value of .001 (*T*[37] = 4.02), and a Cohen's *d* of 1.08, effect size *r* of .47 when using a *p* value of .05 (*T* = 1.80). In our sample of monolinguals (*N* = 10), we get a Cohen's *d* of 2.86, effect size *r* of .82 (large effect size) when using a *p* value of .001 (*T* = 4.30), and a Cohen's *d* of 1.22, effect size *r* of .52 (medium effect size) when using a *p* value of .05 (*T* = 1.83). Such numbers mean that at a stricter threshold (e.g., *T* = 4.02, *p* = .001), more powerful results are presented.

For performing group analyses, random-effects model was used. According to Lindquist (2014, personal communication), it allows to incorporate the correlation into the calculation of the appropriate threshold, based on approximating the distribution of the maximum statistic over the whole image. The data was resampled to 2 x 2 x 2-mm voxels and smoothed with a 12-mm Gaussian kernel to decrease spatial noise by making the spatial distribution normal.

4.1.1 Language difference in bilinguals

The contrasts bilinguals reading in Portuguese and English greater than fixation were conducted separately for each of the twelve participants (within-subject design) in each language and then averaged using paired t-tests (between-subjects analysis). In so doing, it is possible to observe which areas were activated in each language greater than fixation. I decided to report in this work clusters with two different *T*-levels: 1.8 and 4.02, and two *p* (probability) levels: $p < .05$ and $p < .001$. I acknowledge that in Psycholinguistics, researchers generally report results at $p < .05$, and in Cognitive Neuroscience, scholars usually report results at $p < .001$. Psycholinguistics studies deal with behavioral data while cognitive neuroscientists deal with the brain, with more than 20,000 voxels. As explained previously in this section, a more stringent

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negative). Lindquist (2014, personal communication) explains that the probability that a hypothesis test will correctly reject a false null hypothesis is the power of the test.

[36] Cohen's *d* and effect size *r* were calculated online (http://www.uccs.edu/~lbecker/).

[37] Statistically, the greater the magnitude of *T*, the greater the evidence against the null hypothesis. The *T* value varies according to the statistical test and the degrees of freedom. When comparing reading > fixation, we have 11 degrees of freedom with the bilinguals and 9 with the monolinguals. When comparing bilinguals > monolinguals reading in Portuguese, we have 20 degrees of freedom.

threshold elicits more powerful results, and thus, less prone to errors. A less strict threshold includes 'noise'[38] in the data. I chose to report both thresholds to observe such issues. Figures 4.1 and 4.2 and tables 4.1 and 4.2 show the clusters that were elicited by using two different thresholds (T = 1.80, p <.05; and T = 4.02, p <.001).

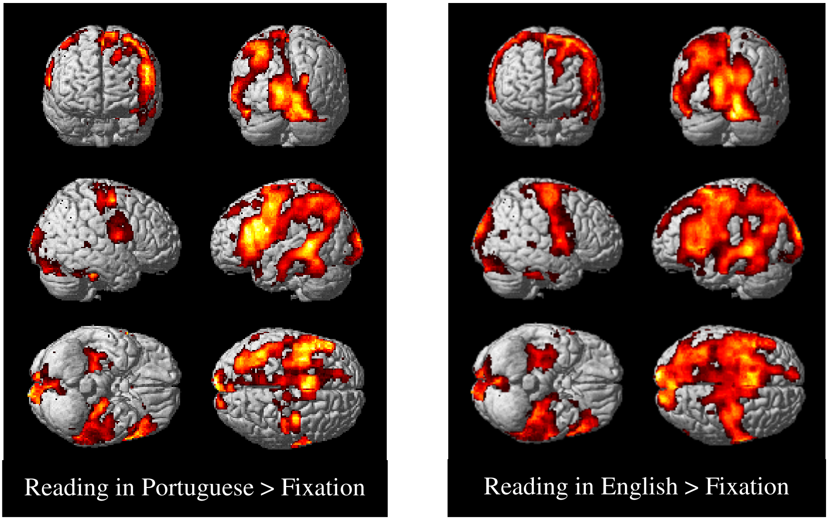


Figure 4.1. Brain renderings of the conditions bilinguals reading in Portuguese (left) and reading in English (right) greater than fixation (SPM8; p <.05, uncorrected; T = 1.80; extent threshold voxels = 15)

[38]According to Huettel et al. (2009), noise in fMRI relates to nonmeaningful changes. They explain the concept of noise with an analogy that an individual is at a party and asks someone a question. There a lot of loud sounds which interfere with the ability of such an individual to hear the response. In this situation the question would be the stimulus and the response to the question would be the signal, while the sounds would be called noise.

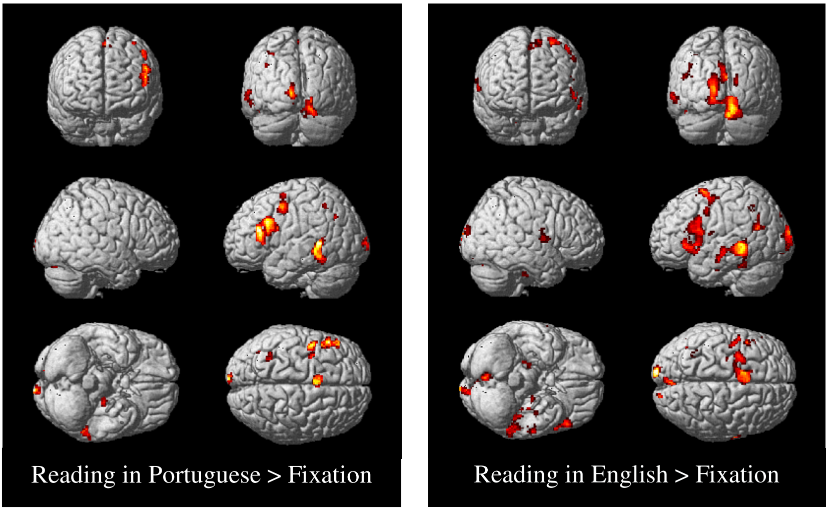


Figure 4.2. Brain renderings of the conditions bilinguals reading in Portuguese and reading in English greater than fixation (SPM8; p <.001, uncorrected; T = 4.02; extent threshold voxels = 15)

Table 4.1. Group labeling of activation for bilinguals reading in Portuguese greater than fixation and reading in English greater than fixation

Portuguese > Fixation						
Centroid and adjacent activation	Cluster size (voxels)	*T* (12)	BA	MNI Coordinate		
				x	*y*	*z*
Frontal						
L middle frontal	35	2.25	BA10	-32	44	14
Temporal						
L precuneus	47,837	7.35		-20	-46	2
R hippocampus		7.05		30	-38	6
L post middle temporal		6.87		-34	-52	8
Subcortical						
R caudate	18	2.75		20	28	6

English > Fixation						
Centroid and adjacent activation	Cluster size (voxels)	*T* (12)	BA	MNI Coordinate		
				x	*y*	*z*
Frontal						
R inferior/medial	77	2.33	BA46	18	30	12

frontal						
R middle frontal (PFC)		2.27	BA46	26	34	12
R superior frontal		2.04	BA10	24	24	18
L inferior frontal (orbitalis)	34	2.70	BA47	-20	12	-26
L cingulate	18	2.36	BA24	-10	2	30
L anterior cingulate		1.89	BA24	-2	8	26
Parietal						
R postcentral	35	2.19	BA40	32	-38	60
R precuneus	16	2.15	BA7	28	-52	34
Temporal						
L middle temporal	65,595	8.86	BA22	-52	-42	-8
R cerebellum		8.65		8	-72	-24
R lingual		8.19	BA19	20	-46	4
R middle temporal	50	2.54	BA39	56	-70	14
R inferior temporal	16	2.38	BA20	58	-6	-34

Note: Clusters of voxels significant at p <.05, uncorrected, T = 1.80, extent threshold = 15 voxels. Group contrasts of bilinguals reading in Portuguese with fixation and of bilinguals reading in English with fixation. Region labels apply to the entire extent of the cluster with peak maxima designated by first locale cited. T-values and MNI coordinates are for the peak activated voxel in each cluster. Labels are given in AAL system (Automated Anatomical Labeling System) as implemented in SPM8.

Table 4.2. Group labeling of activation for bilinguals reading in Portuguese greater than fixation and reading in English greater than fixation

Portuguese > Fixation						
Centroid and adjacent activation	Cluster size (voxels)	*T* (12)	BA	MNI Coordinate		
				x	*y*	*z*
Frontal						
L inferior frontal (opercularis)	901	6.76	BA 44	-48	18	32
L inferior frontal (triangularis)		6.27	BA45	-42	26	14
L inferior frontal (opercularis)		6.16	BA44	-38	8	22
L supplementary motor area	195	6.27	BA6	-6	8	56
L precentral	144	5.68	BA6	-46	-2	48
R superior frontal sulcus	124	6.01	BA24	22	-2	34
R putamen		4.96		30	-2	12
R caudate		5.8		24	-6	20
L middle frontal	27	5.58		-22	-6	26
L precentral	34	4.95	BA6	-36	0	62
R precentral	20	5.48		36	-6	26

Parietal						
L inferior parietal (IPS)	91	5.01	BA7	-30	-54	46
L angular	16	4.66	BA 39	-38	-66	36
Temporal						
L hippocampus	1,001	7.35		-20	-46	2
L middle temporal		6.87		-34	-52	8
L parahippocampal		6.56		-28	-56	2
R hippocampus	287	7.05		30	-38	6
R hippocampus		5.85	BA20	36	-42	0
R hippocampus		5.81	BA19	22	-40	6
L hippocampus	43	5.02	BA36	-22	-20	-20
L hippocampus	16	5.38		-30	-34	-6
Occipital						
R lingual	211	5.59	BA18	16	-80	-16
R calcarine		4.66		18	-92	-4
L middle occipital	136	5.43	BA18	-8	-106	8
L lingual	48	4.45	BA18	-8	-82	-8
L posterior cingulate (calcarine)	17	4.41	BA31	-6	-70	12
Cerebellum						
R cerebelum	22	4.79		30	-68	-32

English > Fixation						
Centroid and adjacent activation	Cluster size (voxels)	*T* (12)	BA	MNI Coordinate		
				x	*y*	*z*
Frontal						
L supplementary motor area	750	6.78	BA6	-6	10	56
L superior frontal		6.6	BA6	-12	4	56
L middle frontal		5.36	BA6	-32	4	64
L inferior frontal	765	5.86	BA44	-52	12	-2
L inferior frontal (triangularis)		5.58	BA47	-50	26	0
L inferior frontal (triangularis)		5.5	BA44	-44	16	24
R precentral	90	5.58	BA6	42	-6	22
L precentral	54	5.68	BA6	-46	-6	56
L precentral	48	4.91	BA6	-52	0	44
L precentral	16	5.12	BA4	-46	-4	14
L precentral	15	4.19	BA4	-34	-20	56
Parietal						
L inferior parietal (IPS)	81	4.75	BA7	-30	-54	40
Temporal						
L middle temporal	886	8.86	BA22	-52	-42	-8
		6.49	BA21	-62	-44	-2

		5.50	BA22	-40	-30	-8
L middle temporal	179	5.89	BA 39	-40	-58	20
		5.01	BA39	-50	-62	20
L superior temporal		4.93		-38	-50	10
R Heschl	42	5.48	BA22	66	-2	6
R postcentral (parietal)		5.07		68	-6	18
R hippocampus	37	5.43		18	-20	-36
		4.76	BA20	24	-26	-34
L inferior temporal	31	4.77	BA20	-36	-12	-28
L hippocampus	16	4.84	BA20	-32	-30	-12
Occipital						
R lingual	1,749	8.65	BA18	8	-76	-24
		6.61	BA18	12	-78	-16
L posterior cingulate (calcarine)	841	6.75	BA19	-16	-50	4
L cuneus		5.43	BA17	0	-78	20
L posterior cingulate		5.42	BA19	-12	-58	20
R calcarine	485	8.19	BA19	20	-46	4
R lingual		6.52	BA30	26	-54	2
R superior occipital	46	4.69	BA18	16	-98	16
L parahippocampal	32	4.48	BA30	-26	-56	2
L fusiform		4.28	BA17	-28	-64	2
L parahippocampal	21	5.64	BA28	-22	-16	-24

Note: Clusters of voxels significant at p <.001, uncorrected, T = 4.02, extent threshold = 15 voxels. Group contrasts of bilinguals reading in Portuguese with fixation and of bilinguals reading in English with fixation. Region labels apply to the entire extent of the cluster with peak maxima designated by first locale cited. T-values and MNI coordinates are for the peak activated voxel in each cluster. Labels are given in AAL system (Automated Anatomical Labeling System) as implemented in SPM8.

By observing the two sets of figures and tables, it is possible to notice the effects of setting stricter and less strict thresholds. As predicted by Woo and colleagues (2014), the less strict threshold used here (T = 1.80, p <.05) elicited few but very large clusters. In the contrast Portuguese > fixation, we find three clusters, a huge one with its peak located in the left precuneus. From its 47,837 voxels the majority of clusters are located in the left hemisphere (30,393; 11,177 in the right hemisphere). From them, 14,891 are located in the frontal lobe; 7,012 in the occipital lobe; 6,541 in the temporal lobe; and 5,118 in the parietal lobe (as reported by *xjView*[39]). In the contrast English > fixation, we find eight clusters, one of them is a huge cluster with its peak located in the

[39]The *xjView* software is a viewing tool implemented in SPM8. It allows the researcher to view multiple images at a time and to access anatomy description with a single mouse click. Information available at <http://www.fil.ion.ucl.ac.uk/spm/ext/>

left middle temporal region. From the 65,595 voxels, the majority of clusters are located in the left hemisphere (39,368; 18,495 in the right hemisphere). From them, 20,889 are located in the frontal lobe; 10,697 in the occipital lobe; 9,427 in the temporal lobe; and 8,260 in the parietal lobe. As these large clusters present clusters of voxels in all lobes and hemispheres, it is complex to draw specific spatial inferences between function and location.

With a stricter threshold (T = 1.80, p <.001), we can find 18 clusters in the Portuguese > fixation contrast and 20, in the English > fixation contrast. The four lobes present significant clusters and spatial locations are more specific (that is the reason why we now have more clusters and less voxels in each cluster if compared to the less strict threshold). Let us observe the overlap between reading in the two languages contrasted to fixation as presented in figures 4.3 and 4.4 (T = 1.80, p <.05; and T = 4.02, p <.001).

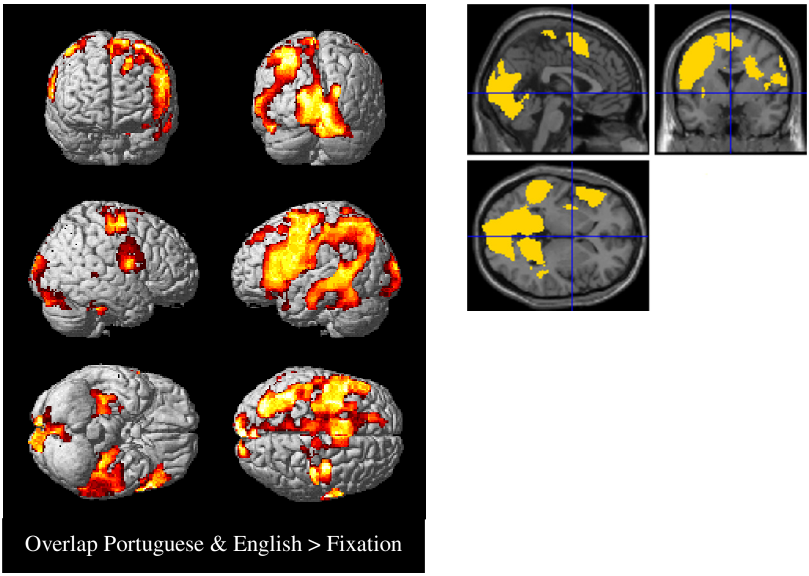


Figure 4.3. Brain rendering and section view of the overlap between bilinguals reading in the two languages in contrast to fixation (SPM8; p <.05, uncorrected; T = 1.80; extent threshold voxels = 15)

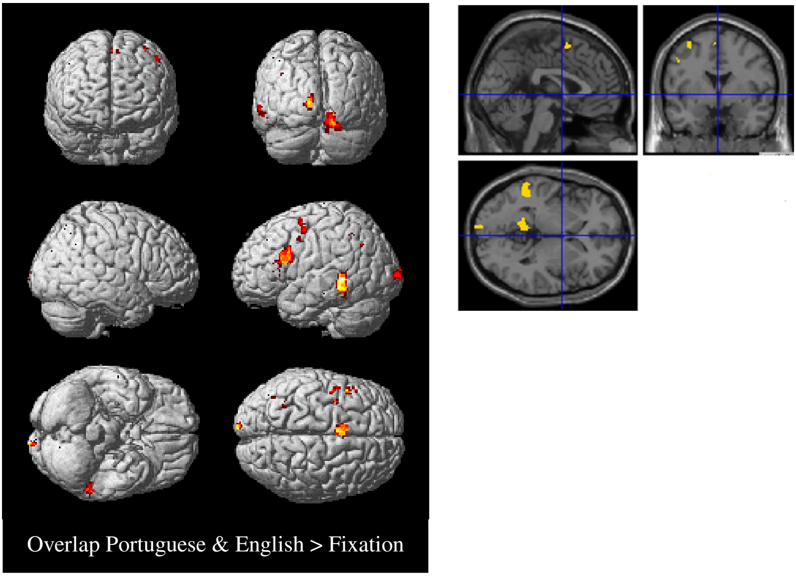


Figure 4.4. Brain rendering and section view of the overlap between bilinguals reading in the two languages in contrast to fixation (SPM8; p <.001, uncorrected; T = 4.02; extent threshold voxels = 15)

From the tables and images, one may conclude that both languages, L1 and L2, in bilinguals, display overlapping activity (the yellow color in the figure stands for a higher number of overlapping voxels) in frontal areas, particularly in left motor areas, left IPS (intra-parietal sulcus), and right lingual. Contrasted to fixation, reading in the L2, English, recruits more voxels and adjacent areas especially in left frontal, bilateral temporal and occipital regions (visual areas) than reading in the L1. By observing the figures, it is possible to say that the L2 engages more posterior temporal areas than the L1.

On top of what was shown, activations of bilinguals reading in each language greater than fixation were contrasted in order to provide the language difference (T = 1.80, p <.05; T = 4.02, p < .001; paired t test, images masked for deactivations). By this means, one can see which areas and to what extent they are activated in each language while bilinguals read sentences, shown in figures 4.5 and 4.6, and tables 4.3 and 4.4.

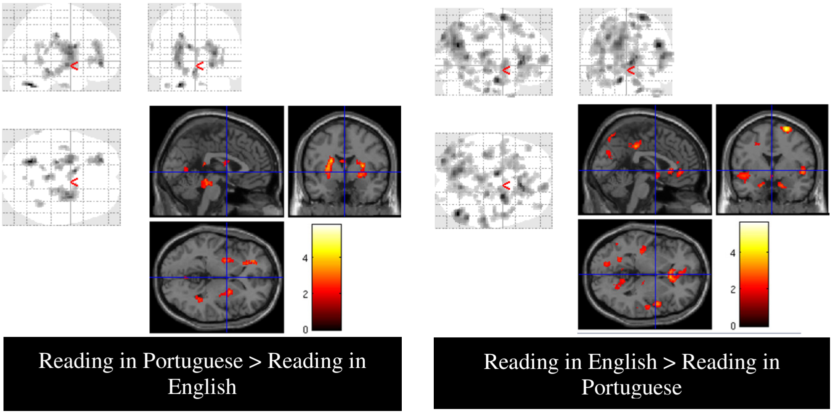


Figure 4.5. Glass views and section views of the contrasts between bilinguals reading in the two languages (SPM8; p <.05, uncorrected; T = 1.80; extent threshold voxels = 15)

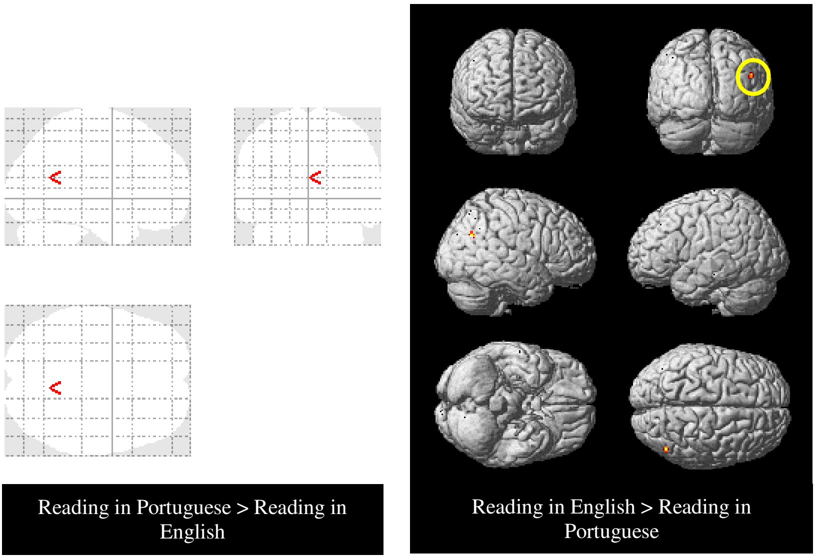


Figure 4.6. Glass view and brain rendering of the contrasts between bilinguals reading in the two languages (SPM8; p <.001, uncorrected; T = 4.02; extent threshold voxels = 15)

Table 4.3. Group labeling of activations for bilinguals reading in Portuguese-English and English-Portuguese

Portuguese > English						
Centroid and adjacent activation	Cluster size (voxels)	*T* (12)	BA	MNI Coordinate		
				x	*y*	*z*
Frontal						
L middle frontal (PFC)	472	4.21	BA11	-24	44	-2
L middle frontal		3.43	BA46	-28	40	20
L superior frontal		3.41	BA9	-22	40	12
L cingulate	63	4.05	BA31	-20	-20	36
		2.14	BA24	-16	-20	28
Parietal						
R posterior cingulate	31	2.70	BA23	2	-36	14
L posterior cingulate	26	2.80	BA31	-12	-40	20
L posterior cingulate		1.95	BA23	-16	-42	28
Temporal						
R middle temporal	109	2.85	BA22	38	-44	2
R fusiform		2.56	BA39	40	-46	16
L inferior temporal	42	2.74	BA20	-42	-8	-34
L superior temporal	31	2.56	BA22	-64	-48	22
Occipital						
R lingual	28	2.36	BA18	2	-66	2
Subcortical						
R putamen	914	4.34		28	0	10
R putamen		3.91		24	-6	-6
R caudate		3.37		20	-18	24
L caudate	698	4.26		-22	-2	20
L putamen		3.57		-28	2	8
Amygdala		2.93		-14	-16	-12
L caudate	128	4.48		-8	6	20
R thalamus		2.31		2	-2	8
L thalamus		2.30		-2	-4	16
Cerebellum						
L cerebellum	146	3.98		-2	-32	-16
L cerebellum	119	5.84		-22	-58	-34
R cerebellum	20	2.46		10	-58	-32

English > Portuguese						
Centroid and adjacent activation	Cluster size (voxels)	*T* (12)	BA	MNI Coordinate		
				x	*y*	*z*
Frontal						

R anterior cingulate	1212	4.58		6	26	4
L middle frontal	473	3.04	BA8	-34	20	56
L superior frontal		2.98	BA6	-18	16	54
L superior frontal		2.71	BA6	-22	8	66
L mid cingulate	453	3.42	BA31	-2	-30	40
L precuneus (parietal)		2.39	BA5	-20	-40	48
L postcentral		2.19	BA4	-14	-38	54
R superior frontal	385	4.87	BA6	22	0	68
		3.86	BA6	30	4	68
		2.79	BA6	6	-18	72
R superior medial frontal	181	3.32	BA10	8	62	10
L middle frontal (PFC)	78	2.64	BA46	-46	38	20
R superior frontal	70	2.76	BA6	16	16	52
		2.09	BA6	24	14	56
R orbital frontal	59	2.79	BA11	38	56	-12
		2.17	BA10	36	48	-6
R superior frontal	47	2.79	BA9	18	44	42
		2.19	BA6/8	12	32	42
L inferior frontal (orbitalis)	47	2.34	BA47	-32	20	-20
		2.11	BA47	-30	30	-20
		1.93	BA47	-30	18	-28
L anterior cingulate	38	2.32	BA25	0	2	-10
L superior frontal	31	2.31	BA6	-24	-2	44
L supplementary motor area	31	2.25	BA6	-14	-8	66
L medial frontal		1.93	BA6	-12	-2	54
R superior frontal	23	2.82	BA8	32	26	58
R precentral	23	2.15	BA4	10	-28	60
L precentral	16	2.13	BA4	-34	-16	54
Parietal						
L precuneus	3607	4.23	BA7	-10	-72	30
		4.16	BA19	-14	-62	30
		4.01	BA19	-28	-88	38
R precuneus	96	2.29	BA7	12	-74	34
L inferior parietal	31	2.16	BA40	-50	-52	54
Temporal						
R superior temporal	376	3.86	BA42	56	-28	16
R posterior superior temporal		2.71	BA22	54	-30	8
R superior temporal		2.12	BA42	44	-32	14
L hippocampus	370	3.39		-36	-26	-6
R insula		3.30	BA41	-36	-24	20

L hippocampus		3.27		-34	-18	-8
R superior temporal	286	3.38	BA22	50	2	-2
R middle temporal		2.38	BA22	56	-14	0
R superior temporal		2.24	BA22	52	-10	-6
L superior temporal	274	2.69	BA22	-46	-2	-8
		2.68		-40	4	-16
		2.52		-38	0	-6
L hippocampus	211	4.85	BA36	-10	-8	-22
		2.76	BA36	-18	0	-26
		2.38	BA36	-28	4	-22
R inferior temporal	71	2.87	BA20	50	-10	-38
R parahippocampal		2.58	BA20	42	-12	-38
L fusiform	47	2.52	BA20	-36	-20	-26
R hippocampus	46	3.56		20	-22	-34
L inferior temporal	45	3.05	BA37	-56	-62	-16
R middle temporal pole	28	2.70	BA21	46	12	-44
L middle temporal	22	2.19	BA37	-52	-60	-4
Occipital						
R angular	833	5.61	BA39	48	-66	28
R superior temporal		4.09	BA39	54	-52	12
R middle temporal		3.03	BA39	56	-60	16
L lingual	148	2.67	BA17	-16	-82	2
L middle occipital		2.38	BA18	-16	-94	-12
L lingual		1.92	BA18	-14	-86	-8
R middle/inferior occipital	45	2.16	BA18	26	-98	22
Subcortical						
R amygdala	89	3.04	BA36	12	-6	-22
R thalamus	16	2.23		16	-38	6
R thalamus	22	2.01		16	-20	8
Cerebellum						
L cerebellum	116	2.70		-28	-48	-26
		2.24		-32	-56	-28
R cerebellum	39	2.42		30	-36	-36
R cerebellum	32	2.17		10	-36	-20

Note: Clusters of voxels significant at p <.05, uncorrected, T = 1.80, extent threshold = 15 voxels. Group contrasts of Portuguese-English reading and English-Portuguese reading in bilinguals. Region labels apply to the entire extent of the cluster with peak maxima designated by first locale cited. T-values and MNI coordinates are for the peak activated voxel in each cluster. Labels are given in AAL system (Automated Anatomical Labeling System) as implemented in SPM8.

Table 4.4. Group labeling of activations for bilinguals reading in Portuguese-English and English-Portuguese

Portuguese > English						
Centroid and adjacent activation	Cluster size (voxels)	*T* (12)	BA	MNI Coordinate		
				x	*y*	*z*
No clusters active						

English > Portuguese						
Centroid and adjacent activation	Cluster size (voxels)	*T* (12)	BA	MNI Coordinate		
				x	*y*	*z*
Occipital						
R middle occipital	16	5.61	BA39	48	-66	28

Note: Clusters of voxels significant at p <.001, uncorrected, T = 4.02, extent threshold = 15 voxels. Group contrasts of Portuguese-English reading and English-Portuguese reading in bilinguals. Region labels apply to the entire extent of the cluster with peak maxima designated by first locale cited. *T*-values and MNI coordinates are for the peak activated voxel in each cluster. Labels are given in AAL system (Automated Anatomical Labeling System) as implemented in SPM8.

At a less strict threshold (p <.05) the contrasts L1-L2 reading and L2-L1 reading seem to corroborate what was aforementioned. Reading in English, the L2, engages clusters in right frontal areas, bilateral temporal and occipital regions as well as the left precuneus in the parietal lobe. The left hippocampus cluster shown in the table is adjacent to the fusiform gyrus, notably implicated in letter/word recognition in deep orthographies. On the other hand, reading in Portuguese, the L1, elicits more subcortical activation, the bilateral putamen (part of the basal ganglia) and the left cerebellum. At a more stringent threshold (p <.001), the contrast L1-L2 does not elicit any active clusters while the contrast L2-L1 only reveals a small cluster of 16 voxels in the right middle occipital region, adjacent to the angular gyrus. From this analysis, it seems that the brain activation converges for the L1 and the L2. These results will be discussed in light of the literature in the next chapter, Discussion. Now, let us turn to the results of monolinguals reading and the differences in processing the L1 among monolinguals and bilinguals.

4.1.2 Differences in processing L1 in bilinguals and monolinguals

The contrast monolinguals reading in Portuguese greater than fixation was conducted separately for each of the ten participants (within-subject design) and then averaged using paired t-tests (between-subjects analysis). By this means, it is possible to inspect which areas were activated by monolinguals when reading in Portuguese. Figure 4.7 and tables 4.5 and 4.6 show the active clusters (T = 1.83, p <.05 and T = 4.30, p <.001).

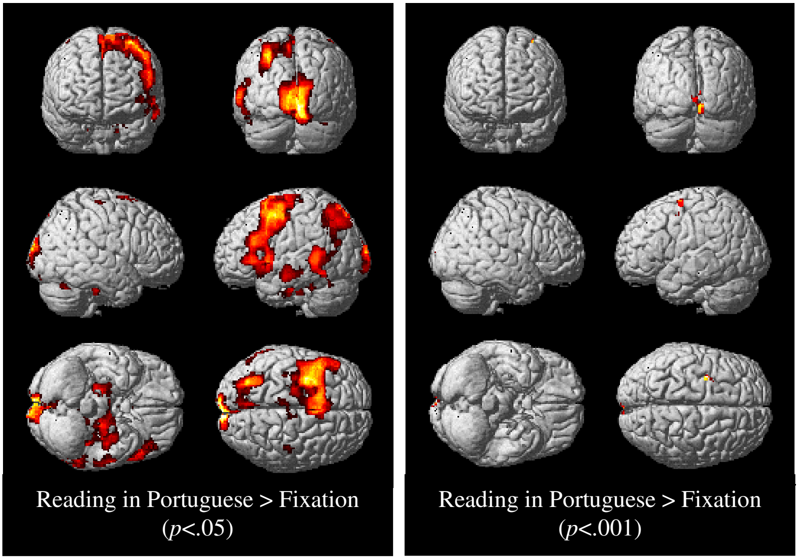


Figure 4.7. Brain renderings of the condition monolinguals reading in Portuguese greater than fixation (SPM8; p <.05 (left) and p <.001 (right), uncorrected; T = 1.83 (left) and T = 4.30 (right); extent threshold voxels = 15)

Table 4.5. Group labeling of activation for monolinguals reading in Portuguese greater than fixation

Monolingual reading Portuguese > Fixation						
Centroid and adjacent activation	Cluster size (voxels)	T (10)	BA	MNI Coordinate		
				x	y	z
Frontal						
L superior frontal	20,090	5.95	BA4	-32	-4	66
L cingulate		5.69	BA24	-16	-8	32
R lingual (occipital lobe)		5.68	BA18	8	-84	-8
L superior frontal/precentral	101	2.34	BA4	-8	-30	68
L postcentral and precentral gyri		2.07	BA3	-8	-38	70

R primary motor cortex		2.05	BA4	8	-18	66
Parietal						
L inferior parietal (IPS)	1,511	4.48	BA7	-30	-70	44
		4.45	BA7	-22	-70	62
		4.21	BA7	-4	-72	60
R precentral	36	2.84	BA1	46	-22	66
Temporal						
L inferior temporal	1,240	3.94	BA22	-52	-50	-12
L fusiform		3.85	BA37	-42	-38	-24
L middle temporal		3.19	BA22	-66	-46	0
L middle temporal	339	3.56	BA22	-56	-8	-16
L middle temporal		3.14	BA22	-58	-12	-8
L superior temporal		2.77	BA22	-62	-30	-12
R parahippocampal	307	3.45	BA36	20	-24	-28
R hippocampus		2.82	BA36	22	-12	-24
Cerebellum						
Cerebellum	130	3.15		2	-36	-26
		2.53		-4	-46	-32
		2.26		10	-40	-20

Note: Clusters of voxels significant at p <.05, uncorrected, T = 1.83, extent threshold = 15 voxels. Group contrast of Portuguese reading with fixation in monolinguals. Region labels apply to the entire extent of the cluster with peak maxima designated by first locale cited. T-values and MNI coordinates are for the peak activated voxel in each cluster. Labels are given in AAL system (Automated Anatomical Labeling System) as implemented in SPM8.

Table 4.6. Group labeling of activation for monolinguals reading in Portuguese greater than fixation

Monolingual reading Portuguese > Fixation						
Centroid and adjacent activation	Cluster size (voxels)	*T* (10)	BA	MNI Coordinate		
				x	*y*	*z*
Frontal						
L middle frontal	35	5.19	BA6	-28	4	46
L superior frontal	27	5.95	BA4	-32	-4	66
L cingulate	19	5.69	BA24	-16	-8	32
Occipital						
R lingual	58	5.68	BA18	8	-84	-8
L calcarine	34	5.17	BA17	2	-100	0
L superior occipital		4.67	BA17	8	-98	8
R lingual		4.39	BA18	6	-96	-8
Subcortical						
L thalamus	45	5.28		-18	-38	12

L posterior caudate		4.49	-26	-38	6
Cerebellum					
L cerebellum	17	5.43	-8	-34	-12

Note: Clusters of voxels significant at *p* <.001, uncorrected, *T* = 4.30, extent threshold = 15 voxels. Group contrast of Portuguese reading with fixation in monolinguals. Region labels apply to the entire extent of the cluster with peak maxima designated by first locale cited. *T*-values and MNI coordinates are for the peak activated voxel in each cluster. Labels are given in AAL system (Automated Anatomical Labeling System) as implemented in SPM8.

As observed in the previous subsection, the less strict threshold (*T* = 1.83, *p* <.05) elicits clusters with a larger number of voxels and less spatially specific. From the 20,090 voxels in the contrast Portuguese > fixation (*T* = 1.83, *p* <.05), the majority of clusters are located in the left hemisphere (13,388; 3,833 in the right hemisphere). From them, 7,244 are located in the frontal lobe; 3,824 in the occipital lobe; 849 in the temporal lobe; and 59 in the parietal lobe. As well, there are large clusters in the IPS, temporal regions and the cerebellum. With a stricter threshold (*T* = 4.30, *p* <.001), monolinguals reading in Portuguese activate (greater than fixation) clusters in the left frontal lobe, bilateral occipital, and left-lateralized subcortical and cerebellum regions.

In order to investigate whether there are differences among monolinguals and bilinguals reading in Portuguese, the brain activation of each group reading in Portuguese (greater than fixation) was contrasted. This second level analysis was done using 2-sample t-test “to compare mean levels during activation versus mean levels during rest” (Pavlicová et al., 2006, p.275) in two independent samples. This way, it is possible to observe which areas were active while monolinguals were reading Portuguese sentences in contrast with bilinguals; and which areas were active when bilinguals were reading Portuguese sentences in contrast with monolinguals. Figures 4.8 and 4.9 and tables 4.7 and 4.8 show the clusters that survived the statistical tests (*T* = 1.72, *p* <.05 and *T* = 3.55, *p* <.001; images were masked for deactivations).

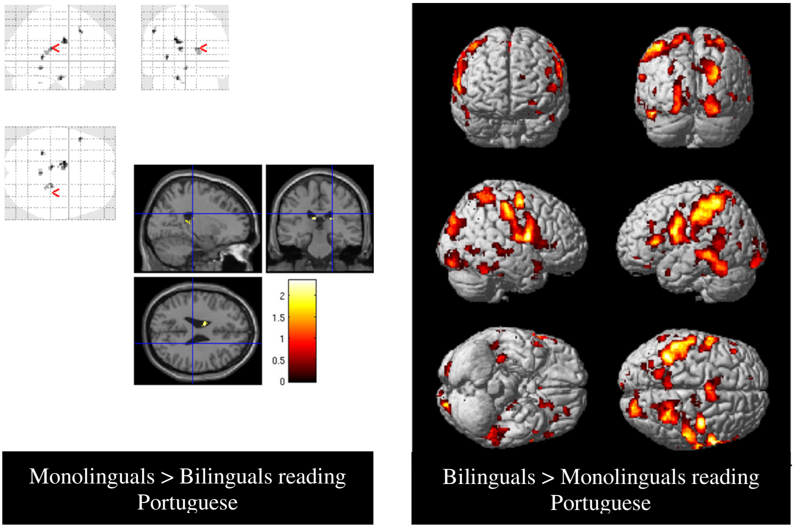


Figure 4.8. Glass views of the condition monolingual Portuguese reading > bilingual Portuguese reading (left) and rendering of the condition bilingual reading in Portuguese > monolinguals reading in Portuguese (right) (SPM8; p <.05, uncorrected; T = 1.72; extent threshold voxels = 5)

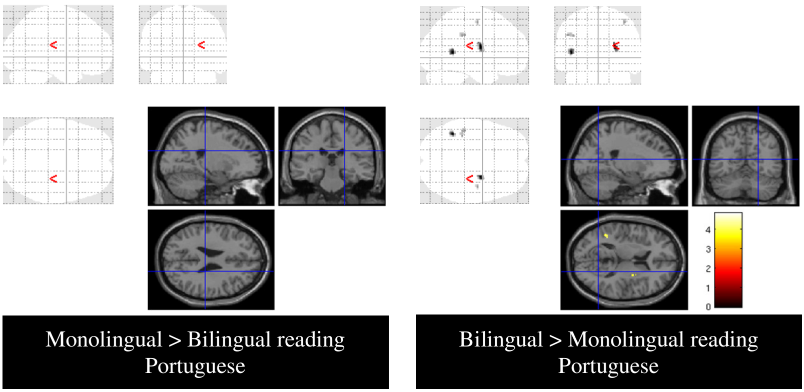


Figure 4.9. Glass views of the conditions monolingual reading in Portuguese > bilingual reading in Portuguese (left) and bilingual reading in Portuguese > monolingual reading in Portuguese (right) (SPM8; p <.001, uncorrected; T = 3.55; extent threshold voxels = 5)

Table 4.7. Group labeling of activation for monolingual reading in Portuguese greater than bilingual reading in Portuguese and bilingual reading in Portuguese greater than monolingual reading in Portuguese

Monolingual reading Portuguese > Bilingual reading Portuguese						
Centroid and adjacent activation	Cluster size (voxels)	*T* (10; 12)	BA	MNI Coordinate		
				x	*y*	*z*
Frontal						
L anterior cingulate	43	2.36	BA24	-16	-6	32
L middle frontal	9	2.23	BA9	-50	18	44
Temporal						
L parahippocampal	14	2.20	BA28	-12	-12	-26
Subcortical						
L thalamus	15	2.19		-8	-26	18
R caudate	13	1.89		20	-34	10
L hippocampus	11	2.18		-28	-42	6
R thalamus	8	2.07		20	-26	18

Bilingual reading Portuguese > Monolingual reading Portuguese						
Centroid and adjacent activation	Cluster size (voxels)	*T* (12; 10)	BA	MNI Coordinate		
				x	*y*	*z*
Frontal						
L inferior frontal (triangularis)	1156	3.24	BA45/ 44	-42	26	10
R anterior cingulate	116	3.05	BA24	20	28	6
R anterior cingulate	99	2.50	BA24	8	0	34
L medial orbitofrontal	42	3.11	BA11	-28	48	-10
L lateral orbitofrontal	30	2.32	BA11	-34	38	-20
R inferior frontal (triangularis)	19	2.17	BA45	56	34	6
L precentral	14	2.06	BA6	-46	-6	52
L superior frontal	11	2.03	BA32	-14	48	24
R anterior cingulate	6	1.89	BA24	2	6	26
L lateral orbitofrontal	5	1.79	BA47/ 11	-40	28	-10
Parietal						
L inferior parietal (IPS)	5279	4.01	BA2	-48	-28	36
L superior parietal	181	2.55	BA7	-18	-60	66
L precuneus	156	2.22	BA5	-6	-48	70
L supramarginal	70	2.60	BA40	-60	-54	24
L superior parietal	48	2.10	BA7	-30	-68	58
L precuneus	21	1.88	BA7	-8	-52	50
L supramarginal	11	1.85	BA40	-62	-38	22
Temporal						
L middle temporal	1951	4.82	BA22	-42	-48	8
R superior temporal	391	3.54	BA22	44	-28	2

R fusiform	230	3.13	BA37	44	-52	-22
R fusiform	100	2.56	BA36	36	-30	-28
R middle temporal	80	2.22	BA37	46	-70	2
R superior temporal pole	61	2.77	BA38	52	18	-20
R superior temporal	61	2.57	BA22	66	-22	0
R fusiform	52	2.24	BA37	26	-50	-26
L middle temporal pole	30	1.99	BA21	-52	10	-28
L parahippocampal	14	2.22	BA36	-34	-32	-30
L middle temporal	14	1.95	BA39	-40	-62	18
R superior temporal pole	9	1.98	BA21	52	10	-34
Occipital						
L middle occipital	94	2.42	BA19	-28	-76	30
L calcarine	41	2.00	BA18	-6	-104	0
L middle occipital	24	2.03	BA39	-44	-74	6
Subcortical						
R putamen	9521	4.83		26	-4	16
R caudate	269	3.72		4	18	4

Note: Clusters of voxels significant at p <.05, uncorrected, T = 1.72, extent threshold = 5 voxels. Group contrast of monolingual reading in Portuguese and bilingual reading in Portuguese. Region labels apply to the entire extent of the cluster with peak maxima designated by first locale cited. T-values and MNI coordinates are for the peak activated voxel in each cluster. Labels are given in AAL system (Automated Anatomical Labeling System) as implemented in SPM8.

Table 4.8. Group labeling of activation for monolingual reading in Portuguese greater than bilingual reading in Portuguese and bilingual reading in Portuguese greater than monolingual reading in Portuguese

Monolingual reading Portuguese > Bilingual reading Portuguese						
Centroid and adjacent activation	Cluster size (voxels)	T (10; 12)	BA	MNI Coordinate		
				x	*y*	*z*
No clusters active						

Bilingual reading Portuguese > Monolingual reading Portuguese						
Centroid and adjacent activation	Cluster size (voxels)	T (12; 10)	BA	MNI Coordinate		
				x	*y*	*z*
Frontal						
R precentral	10	3.94	BA6	42	-8	56
Parietal						
L inferior parietal	23	4.01	BA2	-48	-28	36
Temporal						
L middle temporal	45	4.82	BA22	-42	-48	8
Subcortical						

R putamen	48	4.83	26	-4	16

Note: Clusters of voxels significant at p <.001, uncorrected, T = 3.55, extent threshold = 5 voxels. Group contrast of monolingual reading in Portuguese and bilingual reading in Portuguese. Region labels apply to the entire extent of the cluster with peak maxima designated by first locale cited. T-values and MNI coordinates are for the peak activated voxel in each cluster. Labels are given in AAL system (Automated Anatomical Labeling System) as implemented in SPM8.

The contrast monolingual reading Portuguese–bilingual reading Portuguese suggests that monolinguals do not activate any areas besides the ones activated by bilinguals, since no differences were found at a stricter threshold (T = 3.55, p <.001). At a less strict threshold (T = 1.72, p <.05), small clusters appear in left middle frontal and anterior cingulate areas, left parahippocampal and bilateral subcortical areas. On the other hand, the contrast bilingual reading Portuguese–monolingual reading Portuguese yields, at a stricter threshold (T = 3.55, p <.001), small clusters at bilateral areas: right precentral, right putamen, left IPS and left middle temporal regions. At a less strict threshold (T = 1.72, p <.05), 34 clusters appear. They are located throughout the brain. In the frontal lobe, an emphasis is put on the right anterior cingulate area (that in the previous contrast was located in the left hemisphere); on the bilateral IFG; and the left orbitofrontal region (part of the prefrontal cortex (PFC)). Parietal and occipital clusters are all located in the left hemisphere, while subcortical areas and the majority of temporal clusters, in the right hemisphere. It is significant to highlight the recruitment of the fusiform gyrus, traditionally implicated in word form decoding and right middle and superior temporal areas (BA22), typically associated with word meanings. Such findings seem to converge with the findings from bilinguals reading in the L2, that the L2 engages more voxels and adjacent areas bilaterally than the L1. Here, the bilinguals are reading in their L1 and they seem to exhibit the same behavior, although in different brain locations. Thus, our bilinguals, even when reading in their L1, even at a more stringent threshold, recruit more areas than our monolinguals.

The brain images of monolinguals and bilinguals reading sentences in Portuguese were overlaid in order to allow for a visualization of the overlap of the brain areas involved in reading Portuguese in both samples of participants. Figures 4.10 and 4.11 illustrate the overlap (T = 1.72, p <.05; T = 3.55, p <.001).

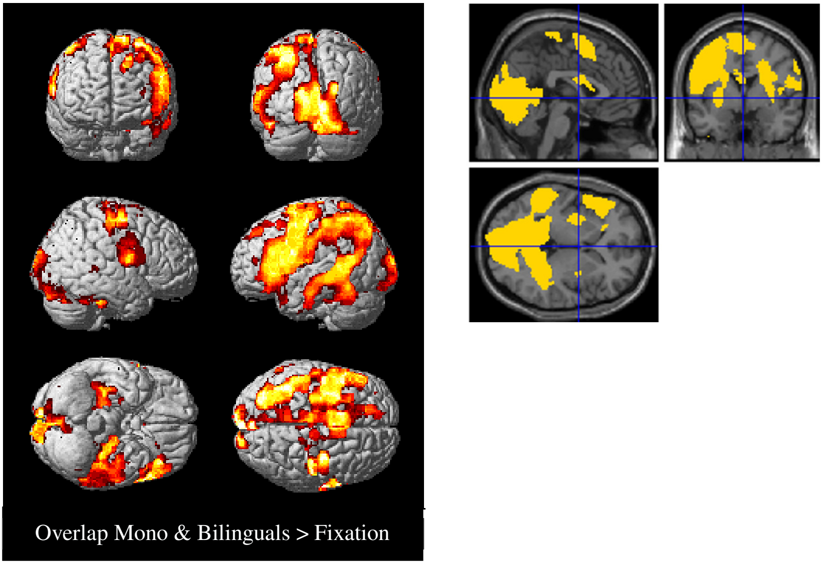


Figure 4.10. Brain renderings of the overlap between monolinguals and bilinguals reading in Portuguese in contrast to fixation (SPM8; p <.05, uncorrected; T = 1.72; extent threshold voxels = 5)

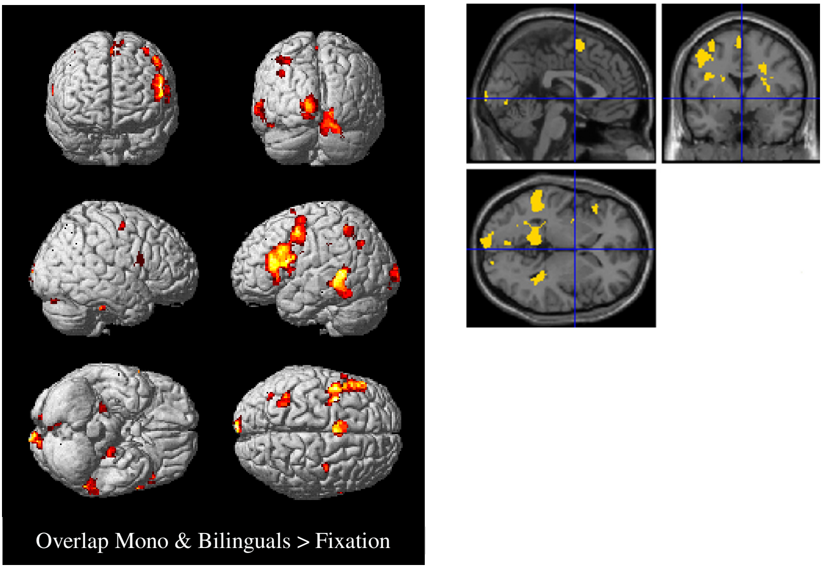


Figure 4.11. Brain renderings of the overlap between monolinguals and bilinguals reading in Portuguese in contrast to fixation (SPM8; p <.001, uncorrected; T = 3.55; extent threshold voxels = 5)

It is possible to note that there is a lot of overlap in all four lobes bilaterally, predominantly in the left hemisphere, at $T = 1.72$ and $p < .05$, between monolinguals and bilinguals reading Portuguese. At $T = 3.55$ and $p < .001$, it is possible to find activation only in left posterior frontal areas, left middle temporal regions and small clusters in left parietal and a few clusters in right-lateralized areas, with highlight to a cluster in the right occipital, bigger than the left hemisphere cluster that, in turn, is closer to the cerebellum. Now let us turn to the effects of individual differences in bilinguals, the topic of the next subsection.

4.1.3 L2 proficiency and WMC: effects on language processing in bilinguals

The analysis reported in the present subsection aimed at investigating whether the language difference may be modulated by individual differences, proficiency in the L2 and WMC. Contrast files (reading > fixation) were generated for each participant in each language and the 2nd level analysis (between-subjects) was built upon these contrast images by paired *t*-test with individual differences as regressors in the model. Figures 4.12 and 4.13 and tables 4.9 and 4.10 present the results concerning proficiency in the L2 ($T = 1.81$, $p < .05$; $T = 4.14$, $p < .001$).

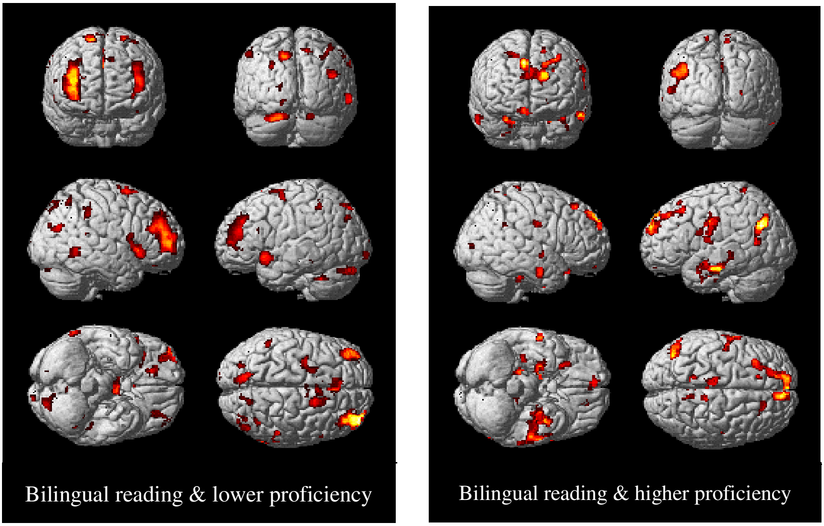


Figure 4.12. Brain views of the active voxels correlated with proficiency in the second language in bilingual reading (SPM8; p <.05, uncorrected; T = 1.81; extent threshold voxels = 15)

Table 4.9. Group labeling of activation for bilinguals reading in English and proficiency in the L2

Bilinguals reading in English with lower L2 proficiency						
Centroid and adjacent activation	Cluster size (voxels)	*T* (12)	BA	MNI Coordinate		
				x	*y*	*z*
Frontal						
R middle frontal	2845	5.60	BA10	42	58	6
R medial superior frontal	563	4.04	BA32	2	26	38
L middle frontal (DLPFC)	562	4.34	BA46	-32	36	-2
R superior frontal	181	3.81	BA6	18	4	68
L precentral	141	2.82	BA6	-30	-6	60
L inferior frontal (triangularis)	30	2.37	BA44	-36	22	20
L SMA	23	2.32	BA6	-2	-4	72
Parietal						
L precuneus	250	3.51	BA7	-12	-72	46
R superior parietal	57	2.38	BA7	16	-72	54
R supramarginal	58	2.60	BA40	54	-38	44
L inferior parietal	44	3.08	BA40	-54	-46	50

(IPS)						
R superior parietal	43	2.17	BA7	40	-60	56
R superior parietal	35	2.63	BA7	38	-76	50
R supramarginal	22	2.58	BA40	64	-38	40
L intraparietal cortex	19	2.30	BA40	-28	-42	28
Temporal						
L superior temporal	248	4.01	BA38	-40	12	-14
R middle temporal	115	6.64	BA21	64	-52	-2
R superior temporal	21	2.36	BA39	48	-40	20
L middle temporal	20	2.27	BA42	-44	-34	-10
Occipital						
R angular	138	3.90	BA39	44	-68	26
L middle occipital (IPS)	52	2.48	BA19	-26	-78	34
L inferior occipital	34	2.26	BA18	-14	-100	-6
L middle occipital	23	3.02	BA17/19	-28	-76	4
L middle occipital	20	2.41	BA18	-16	-106	12
Subcortical						
L caudate	1100	4.23		-12	-18	24
Cerebellum						
L cerebellum	806	5.39		-24	-54	-32
L cerebellum	89	3.04		-6	-26	-10
R cerebellum	42	2.56		18	-82	-26
R cerebellum	35	2.14		14	-56	-16
L cerebellum	15	2.11		-6	-62	-28

Bilinguals reading in English with higher L2 proficiency						
Centroid and adjacent activation	Cluster size (voxels)	*T* (12)	BA	MNI Coordinate		
				x	*y*	*z*
Frontal						
R medial frontal	937	4.38	BA9	8	52	42
L precentral	529	4.26	BA3	-38	-10	30
L medial frontal (precentral)	132	3.90	BA4	-12	-24	60
R medial prefrontal	100	3.72	BA24	2	30	10
R medial frontal	91	2.74	BA11	6	54	-18
R inferior frontal (orbitalis)	73	2.80	BA47	26	18	-28
R superior frontal (PFC)	53	2.60	BA8	16	32	50
R precentral	46	2.34	BA3	48	-10	30
L superior frontal	27	3.11	BA8	-16	26	58
L medial frontal	23	2.21	BA32	-16	44	-2
Parietal						
L precuneus	2063	4.21	BA23	-10	-50	22

L angular	449	3.66	BA39	-42	-70	36
R postcentral	47	2.55	BA4/3	10	-36	74
R precuneus	30	2.40	BA7	10	-56	68
L posterior cingulate	31	2.51	BA31	-6	-34	44
L postcentral	24	2.71	BA7	-14	-48	74
L inferior parietal	24	2.59	BA39/ 40	42	-48	28
Temporal						
L superior temporal	1094	7.49	BA21	-36	2	-20
R parahippocampal	203	3.36	BA35	22	-10	-30
R inferior temporal	98	2.69	BA21	62	-6	-30
R hippocampus	59	3.03	BA20	36	-28	-14
L superior temporal	54	2.90	BA41	-34	-36	6
L superior temporal	43	2.67	BA41	-34	-28	20
R middle temporal	34	3.27	BA22	48	-6	-6
Occipital						
R lingual	36	3.06	BA18	6	-66	-4
R cuneus	16	2.50	BA19	26	-84	6
Subcortical						
R caudate	69	3.24		12	-24	24
R insula	64	2.53		38	-16	0
Cerebellum						
R cerebellum	86	3.42		20	-32	-32
L cerebellum	80	2.72		-8	-34	-20
R cerebellum	49	2.77		8	-36	-10

Note: Clusters of voxels significant at p <.05, uncorrected, T = 1.81, extent threshold = 15 voxels. Group contrasts of bilinguals reading with L2 proficiency. Region labels apply to the entire extent of the cluster with peak maxima designated by first locale cited. T-values and MNI coordinates are for the peak activated voxel in each cluster. Labels are given in AAL system (Automated Anatomical Labeling System) as implemented in SPM8.

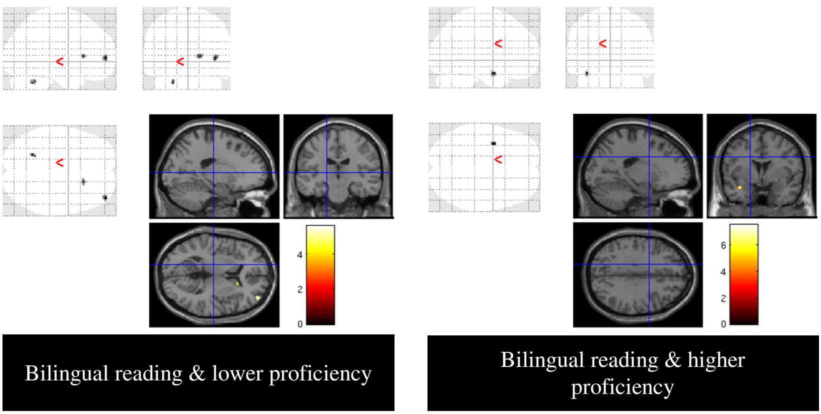


Figure 4.13. Brain views of the active voxels correlated with proficiency in the second language in bilingual reading (SPM8; p <.001, uncorrected; T = 4.14; extent threshold voxels = 15)

Table 4.10. Group labeling of activation for bilinguals reading in English and proficiency in the L2

Bilinguals reading in English with lower L2 proficiency						
Centroid and adjacent activation	Cluster size (voxels)	*T* (12)	BA	MNI Coordinate		
				x	*y*	*z*
Frontal						
R middle frontal	25	5.61	BA10	42	58	6
Subcortical						
R caudate	20	5.18		16	24	8
Cerebellum						
L cerebellum	15	5.40		-24	-54	-32

Bilinguals reading in English with higher L2 proficiency						
Centroid and adjacent activation	Cluster size (voxels)	*T* (12)	BA	MNI Coordinate		
				x	*y*	*z*
Temporal						
L superior temporal	27	7.49	BA38	-36	2	-20

Note: Clusters of voxels significant at $p < .001$, uncorrected, $T = 4.14$, extent threshold = 15 voxels. Group contrasts of bilinguals reading and L2 proficiency. Region labels apply to the entire extent of the cluster with peak maxima designated by first locale cited. *T*-values and MNI coordinates are for the peak activated voxel in each cluster. Labels are given in AAL system (Automated Anatomical Labeling System) as implemented in SPM8.

With a lower, less strict, threshold ($T = 1.81$, $p < .05$), proficiency modulates activation in the four lobes bilaterally. Large clusters appear in greater number in the parietal, temporal and frontal regions, and smaller clusters are found in the occipital lobe, the cerebellum and subcortical regions. With a stricter threshold ($T = 4.14$, $p < .001$), results are more revealing. The more proficient the participants are in English, the more activation they display in the left superior temporal region. The less proficient the participants are in English, the more activation they exhibit in the right middle frontal area, the right caudate and the left cerebellum.

As regards working memory capacity (WMC), figures 4.14 and 4.15 and tables 4.11 and 4.12 present the results ($T = 1.81$, $p < .05$; $T = 3.17$, $p < .005$[40]).

[40]With a stricter threshold, $T = 4.14$ and $p < .001$, no clusters were found.

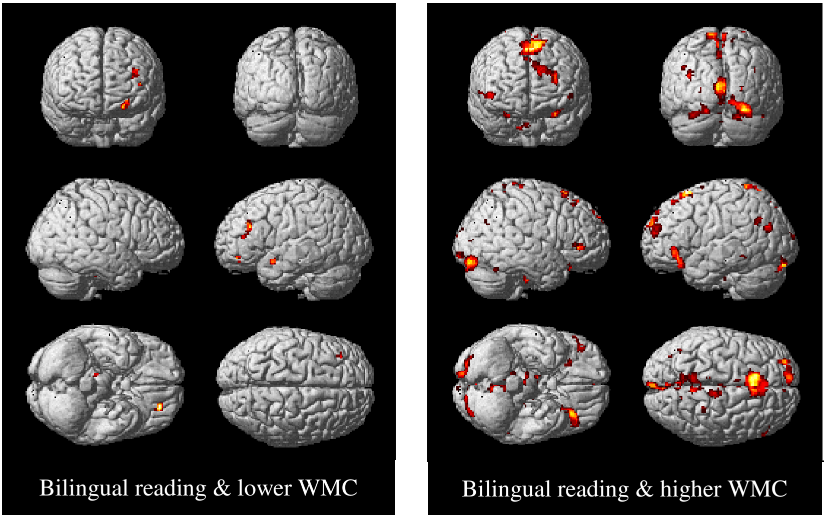


Figure 4.14. Brain views of the active voxels correlated with WMC in bilingual reading (SPM8; $p < .05$, uncorrected; $T = 1.81$; extent threshold voxels = 5)

Table 4.11. Group labeling of activation for bilingual reading and working memory capacity

Bilingual reading with lower WMC						
Centroid and adjacent activation	Cluster size (voxels)	*T* (12)	BA	MNI Coordinate		
				x	*y*	*z*
Frontal						
R anterior cingulate	326	3.93	BA24/ 32	10	28	10
L middle frontal (DLPFC)	108	2.67	BA46	-28	34	14
L superior frontal orbital	56	3.88	BA11	-22	44	-14
R anterior cingulate	47	3.16	BA32	18	2	34
L cingulate	41	2.46	BA31/ 24	-20	-40	26
L inferior frontal (triangularis)	12	2.12	BA46	-42	38	12
R medial frontal orbital	5	1.97	BA24	14	38	-6
Temporal						
L superior temporal pole	21	2.48	BA38	-40	6	-16

R fusiform	5	2.00	BA37	34	-48	-4
Subcortical						
R caudate	32	2.45		0	4	6

Bilingual reading with higher WMC						
Centroid and adjacent activation	Cluster size (voxels)	*T* (12)	BA	MNI Coordinate		
				x	*y*	*z*
Frontal						
L superior frontal	730	4.27	BA6/8	-6	18	60
L inferior frontal (orbitalis)	239	4.06	BA47	-34	28	-14
L superior medial frontal	239	2.92	BA10	-10	62	32
R inferior frontal (orbitalis)	27	2.26	BA47	24	26	-26
R inferior frontal (triangularis)	77	2.62	BA46/47	46	38	0
L anterior cingulate	84	2.72	BA24/32	-12	36	8
L anterior cingulate	33	3.69	BA24	-12	4	32
R superior medial frontal	23	2.08	BA9	4	54	44
R paracentral	67	2.35	BA6	8	-28	72
L paracentral	10	2.14	BA6	-10	-30	60
L supplementary motor area	8	1.91	BA6	-8	0	70
L medial frontal	5	1.89	BA6	-2	-18	64
Parietal						
L precuneus	310	3.69	BA7	-2	-68	62
L angular	85	2.73	BA39	-34	-54	24
R precuneus	52	2.23	BA31	2	-40	40
R postcentral	13	2.16	BA2	26	-36	76
R precuneus	6	2.14	BA7	12	-64	64
L precuneus	5	2.05	BA5	-8	-44	56
L inferior parietal	5	2.29	BA2	-32	-34	38
Temporal						
L hippocampus	374	4.34	BA20	-22	-26	-4
L mid cingulate	118	3.50	BA24	0	-8	38
R middle temporal	24	2.30	BA22	44	-34	4
L middle temporal	18	2.99	BA22	-44	-44	-4
L parahippocampal	12	2.09	BA35	-10	-38	4
R fusiform	8	2.08	BA37	48	-58	-26
L middle temporal	7	2.38	BA21	-54	-44	-10
Occipital						
R lingual	1431	4.36	BA18	0	-68	-2
R lingual	455	3.56	BA18	24	-86	-14

L calcarine	137	2.96	BA17	-28	-62	6
L middle occipital	109	3.01	BA19	-34	-86	-24
L middle occipital	57	2.78	BA19	-36	-72	24
L middle occipital	6	2.23	BA19	-22	-86	6
R middle occipital	6	2.29	BA39	40	-66	28
L middle occipital	5	2.20	BA39	-34	-72	6
Subcortical						
R amygdala	71	2.88		10	-12	-18
L insula	48	2.60		-36	-16	14
R thalamus	22	2.76		14	-14	20
L retrosplenial	18	2.22		-8	-38	14
R caudate	10	2.56		26	-20	20
L putamen	5	2.58		-32	0	2
Cerebellum						
L culmen (vermis)	413	4.22		-4	-56	-24
R cerebellum	24	2.39		20	-72	-28

Note: Clusters of voxels significant at p <.05, uncorrected, T = 1.81, extent threshold = 5 voxels. Group contrasts of bilinguals reading with working memory capacity. Region labels apply to the entire extent of the cluster with peak maxima designated by first locale cited. T-values and MNI coordinates are for the peak activated voxel in each cluster. Labels are given in AAL system (Automated Anatomical Labeling System) as implemented in SPM8.

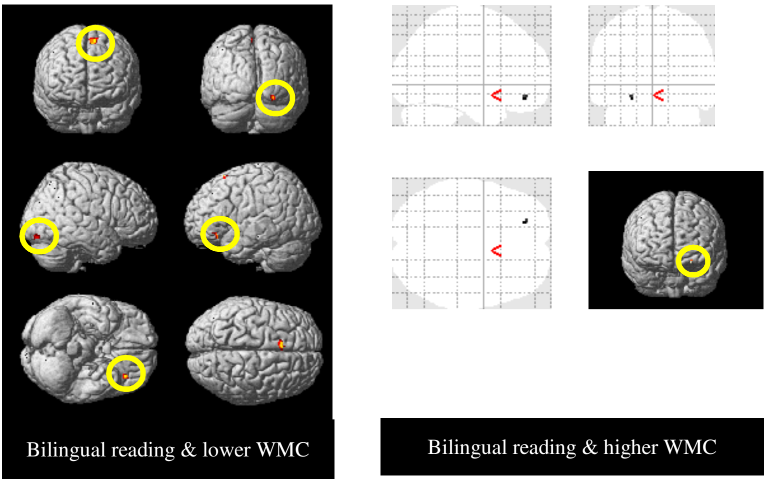


Figure 4.15. Brain views of the active voxels correlated with WMC in bilingual reading (SPM8; p < .005, uncorrected; T = 3.17; extent threshold voxels = 5)

Table 4.12. Group labeling of activation for bilingual reading and working memory capacity

Bilingual reading with lower WMC						
Centroid and adjacent activation	Cluster size (voxels)	*T* (12)	BA	MNI Coordinate		
				x	*y*	*z*
Frontal						
L supplementary motor area	54	4.27	BA6	-6	18	60
L inferior frontal (orbitalis)	19	4.05	BA47	-34	28	-14
Parietal						
L precuneus	5	3.68	BA7	-2	-68	62
Occipital						
R lingual	38	4.35	BA18	0	-68	-2
R lingual	23	3.55	BA18	24	-86	-14
Subcortical						
L thalamus	14	4.33		-22	-26	-4
Cerebellum						
L culmen (vermis)	11	4.22		-4	-56	-24

Bilingual reading with higher WMC						
Centroid and adjacent activation	Cluster size (voxels)	*T* (12)	BA	MNI Coordinate		
				x	*y*	*z*
Frontal						
L superior orbitofrontal (PFC)	5	3.88	BA11	-22	44	-14

Note: Clusters of voxels significant at p <.005, uncorrected, T = 3.17, extent threshold = 5 voxels. Group contrasts of bilinguals with working memory capacity. Region labels apply to the entire extent of the cluster with peak maxima designated by first locale cited. *T*-values and MNI coordinates are for the peak activated voxel in each cluster. Labels are given in AAL system (Automated Anatomical Labeling System) as implemented in SPM8.

Findings suggest that the lower the working memory capacity of our participants are, more activation they exhibit in left frontal areas, as in the supplementary motor area and inferior frontal gyrus (IFG); in the right lingual region; and small clusters in the following left-lateralized areas: precuneus, thalamus and culmen. With a lower threshold (p < .05), it is possible to note a greater participation of right hemisphere frontal, temporal and subcortical regions. On the other hand, the higher the working memory capacity of our participants are, more activation they display in the left superior frontal orbitalis, a small but statistically significant cluster at p = .005. With a lower threshold (p < .05), 42 clusters appear. Among this number of clusters, it is prominent the role of the right hemisphere, although left-lateralized areas show more voxels inside most of the clusters.

4.1.4 WMC: effects on language processing in monolinguals

As it was done with bilinguals, contrast files were generated by reading-fixation for each monolingual (within-subject design) and paired *t*-tests were run (between-subject design) to examine whether WMC correlates with brain activation in monolinguals. Figures 4.16 and 4.17 and tables 4.13 and 4.14 present the results (T = 1.86, p <.05; T = 4.50, p <.001).

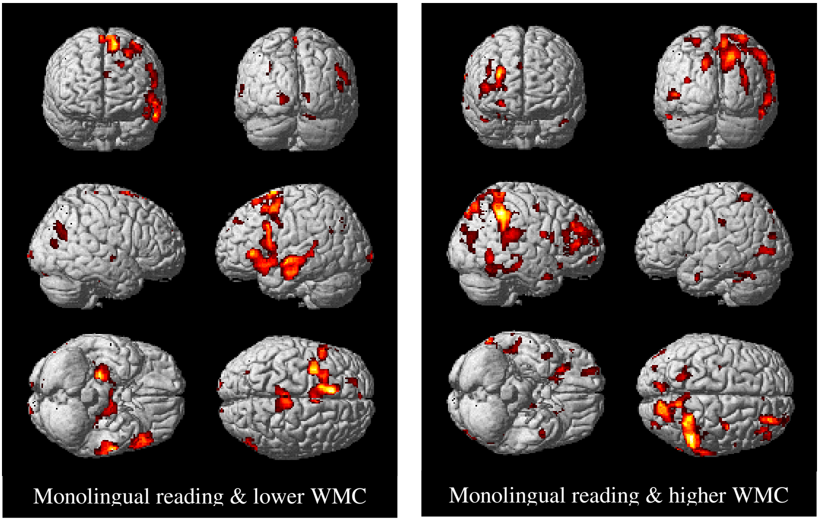


Figure 4.16. Brain views of the active voxels correlated with working memory capacity in monolingual reading (SPM8; p = .05, uncorrected; T = 1.86; extent threshold voxels = 15)

Table 4.13. Group labeling of activation for monolingual reading and working memory capacity

Monolingual reading with lower WMC						
Centroid and adjacent activation	Cluster size (voxels)	*T* (10)	BA	MNI Coordinate		
				x	*y*	*z*
Frontal						
L superior frontal	3538	7.00	BA6	-14	20	38
R supplementary motor area	509	4.61	BA6	0	-28	66
R anterior cingulate	96	3.41	BA24	22	-10	38

L superior frontal	56	2.63	BA9	-18	50	40
L medial superior frontal	27	2.31	BA9	-2	56	28
R anterior cingulate	22	3.10	BA24	14	0	44
Parietal						
L posterior cingulate	218	2.99	BA7	0	-58	30
L angular	81	2.67	BA39	-34	-58	26
L angular	20	2.33	BA39	-30	-74	32
R postcentral	31	2.91	BA3	38	-20	32
Temporal						
L superior temporal	937	9.90	BA21	-56	-10	-6
R middle temporal	533	6.69	BA21/ 37	34	-46	2
R parahippocampal	430	7.16	BA35	26	-26	-26
R middle temporal	154	3.36	BA39	60	-64	20
R middle temporal	40	3.13	BA39	52	-78	14
R hippocampus	22	2.61	BA20	40	-32	-10
R superior temporal	17	2.35	BA22	52	-12	-4
Occipital						
L middle occipital	86	3.25	BA18	-16	-108	-2
L lingual	59	2.79	BA17	-16	-84	2
L inferior occipital	29	2.20	BA18	18	-84	-24
R cuneus	43	3.45	BA18	16	-102	-2
Subcortical						
L caudate	186	6.23		-12	-6	26
R insula	166	4.00		36	-8	16
L putamen	30	2.18		-30	-4	-2
L caudate	22	2.76		-12	14	14
Cerebellum						
L cerebellum	1219	4.72		-6	-38	-8
L cerebellum	49	2.97		-6	-38	-22
R cerebellum	46	2.59		10	-42	-24

Monolingual reading with higher WMC						
Centroid and adjacent activation	Cluster size (voxels)	*T* (10)	BA	MNI Coordinate		
				x	*y*	*z*
Frontal						
R middle frontal	1626	5.24	BA46	28	44	24
R inferior frontal	153	3.61	BA44	44	10	16
R prefrontal cortex	109	3.67	BA6	36	-4	44
R superior frontal	88	2.68	BA10/ 11	26	60	-8
R medial frontal	44	3.54	BA32	6	36	32
R middle frontal	18	2.34	BA6	-32	-12	48
L anterior cingulate	15	3.09	BA24	-8	12	28

Parietal						
R supramarginal	4367	5.39	BA40	48	-42	32
L precuneus	270	4.10	BA7	-12	-72	36
L superior parietal	153	2.98	BA7	-22	-54	60
L posterior cingulate	98	3.46	BA23	-4	-30	28
L inferior parietal	68	3.61	BA2	-46	-30	36
L posterior cingulate	19	2.14	BA31	-10	-34	42
Temporal						
R inferior temporal	671	4.67	BA37	58	-58	-8
L middle temporal	56	2.95	BA21	46	8	-28
L middle temporal	46	3.78	BA21	-48	2	-28
L inferior temporal	41	4.07	BA37	-54	-56	-24
Occipital						
L middle occipital	170	3.29	BA19	-44	-86	0
L superior occipital	45	2.57	BA19	-32	-82	20
Subcortical						
L caudate	138	4.13		-18	24	0
L thalamus	108	3.62		-16	-8	-2
R caudate	65	3.58		10	20	12
Cerebellum						
L cerebellum	193	4.29		-26	-44	-30
L cerebellum	34	2.57		-36	-64	-30

Note: Clusters of voxels significant at p <.05, uncorrected, T = 1.86, extent threshold = 15 voxels. Group contrasts of monolingual reading in Portuguese with working memory capacity. Region labels apply to the entire extent of the cluster with peak maxima designated by first locale cited. T-values and MNI coordinates are for the peak activated voxel in each cluster. Labels are given in AAL system (Automated Anatomical Labeling System) as implemented in SPM8.

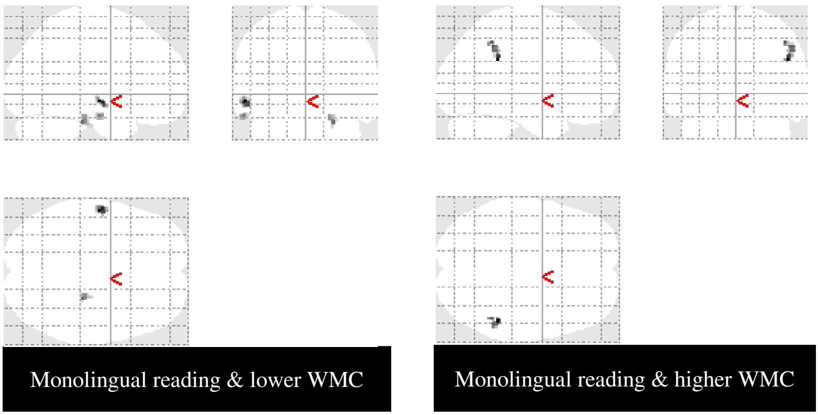


Figure 4.17. Glass brain views of the active voxels correlated with working memory capacity in monolingual reading (SPM8; p = .001, uncorrected; T = 4.50; extent threshold voxels = 15)

Table 4.14. Group labeling of activation for monolingual reading and working memory capacity

Monolingual reading with lower WMC						
Centroid and adjacent activation	Cluster size (voxels)	*T* (10)	BA	MNI Coordinate		
				x	*y*	*z*
Temporal						
L superior temporal	43	9.90	BA22	-56	-10	-6
R parahippocampal	27	7.16	BA35	26	-26	-26
L middle temporal	20	6.90	BA21	-58	-10	-20

Monolingual reading with higher WMC						
Centroid and adjacent activation	Cluster size (voxels)	*T* (10)	BA	MNI Coordinate		
				x	*y*	*z*
Parietal						
R supramarginal	48	5.38	BA40	48	-42	32

Note: Clusters of voxels significant at p <.001, uncorrected, T = 4.50, extent threshold = 15 voxels. Group contrasts of monolinguals reading in Portuguese with working memory capacity. Region labels apply to the entire extent of the cluster with peak maxima designated by first locale cited. *T*-values and MNI coordinates are for the peak activated voxel in each cluster. Labels are given in AAL system (Automated Anatomical Labeling System) as implemented in SPM8.

Findings reveal that the lower the working memory capacity of our monolingual participants are, more activation they exhibit in three clusters in temporal regions, predominantly in the left hemisphere (at p <.001, T = 4.50). The higher the working memory capacity of our monolinguals are, more activation they display in the right supramarginal region. With a lower threshold (p <.05, T = 1.86), one can find 28 clusters all over the brain. The lower the working memory capacity of our monolingual participants are, more activation they display in predominantly left-lateralized frontal, parietal, occipital and subcortical regions and in predominantly right-lateralized temporal regions. For higher working memory capacity, 24 clusters emerge throughout the brain. It is essential to highlight the predominance of right-lateralized frontal areas, and the elevated number of voxels in the right angular, frontal and inferior temporal regions.

4.2 WORD-LEVEL ANALYSIS

The results reported in the present section come from statistical analyses conducted on the whole brain at the word-level on individual and group data by using average pairwise correlations and regression models. The data was resampled to 3 x 3 x 6-mm voxels and smoothed with a 12 x 12 x 6-mm Gaussian kernel to adjust for individual differences in brain anatomy by decreasing spatial noise and making the distribution normal.

4.2.1 Stability analysis: language difference in bilinguals

To analyze the difference in representation location for each language across our 12 bilingual participants, stability maps were computed. We focused on the most stable voxels across all participants. The assumption here is that only the relatively stable voxels provide information about the neural representation of each language. A voxel's stability was computed as the average pairwise correlation between words in each language across the four presentations of each sentence. According to Mason and Just (2015), such voxels exhibit a tuning curve and suggest that they are consistently selective to the processing of words in the context of sentences in each language. As our task involved silent reading, we masked the occipital lobe for this calculation (except for the fusiform gyrus, which is important for reading). Figure 4.18 and table 4.15 present the top stable voxels for reading in each language.

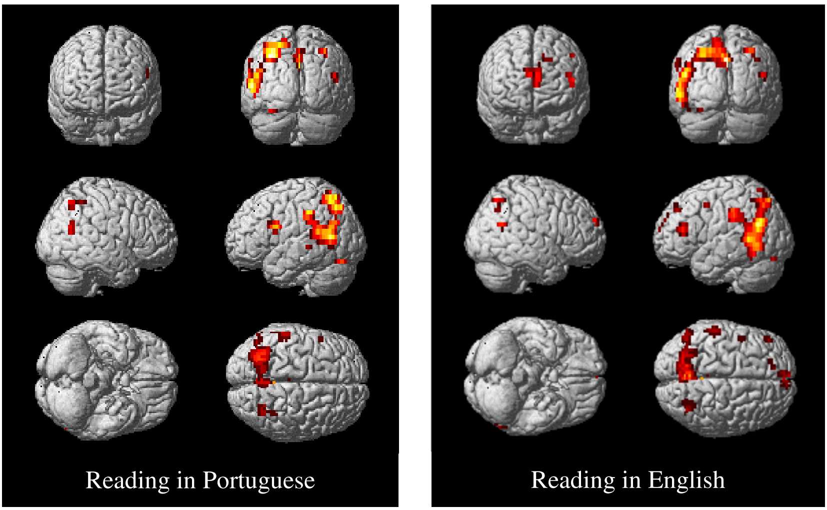


Figure 4.18. Rendered views of the most stable voxels for bilinguals reading in Portuguese and English (SPM8; smoothed data; height threshold = 0.75)

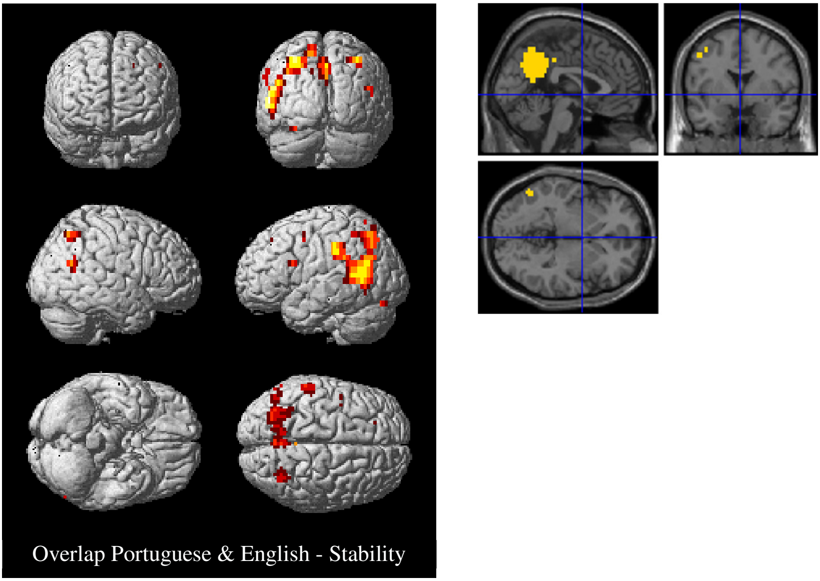


Figure 4.19. Brain rendering and section view of the overlap in stability between bilinguals reading in the two languages (SPM8; smoothed data; height threshold = 0.75)

Table 4.15. Group stability for bilinguals reading in Portuguese and in English

Centroid and adjacent activation	Number of voxels	BA	MNI Coordinate *x*	MNI Coordinate *y*	MNI Coordinate *z*
Top stable voxels in Portuguese reading					
Frontal					
L inferior frontal	55	BA44/9/6	-49.875	6.75	22
L superior frontal	8	BA8	-21.75	34.875	46
L middle frontal	7	BA6	-40.5	-2.625	52
L middle frontal	4	BA9	-40.5	38	28
R inferior frontal	4	BA6	50.125	6.75	34
Parietal					
L precuneus	907	BA7/31	0.125	-58.875	34
R superior parietal	54	BA7/40	31.375	-62	52
L fusiform	26	BA19	-31.125	-74.5	-20
R angular	2	BA19/39	40.75	-71.375	40
Temporal					
R middle temporal	26	BA39	43.875	-62	22
L inferior temporal	3	BA37	-46.75	-55.75	-14
Top stable voxels in English reading					

Centroid and adjacent activation	Number of voxels	BA	MNI Coordinate		
			x	*y*	*z*
Frontal					
L superior medial frontal	112	BA9	-3	56.75	22
L inferior frontal (triangularis)	46	BA45/46	-46.75	34.875	16
L inferior frontal (opercularis)	11	BA44	-46.75	13	22
L middle frontal	10	BA6	-46.75	3.625	46
L supplementary motor area	10	BA6	-3	0.5	64
R inferior frontal (opercularis)	5	BA44	43.875	9.875	34
Parietal					
L precuneus	1097	BA7	0.125	-62	34
R superior parietal	51	BA7	31.375	-65.125	52
L inferior parietal	1	BA7	-43.625	-43.25	46
Temporal					
R superior temporal	29	BA39	47	-58.875	22
Occipital					
L fusiform	9	BA19	-31.125	-80.75	-20

Note: Clusters of stable voxels, smoothed, height threshold = 0.75. Group stability for bilinguals reading in Portuguese and in English. Region labels apply to the entire extent of the cluster with peak maxima designated by first locale cited. MNI coordinates are for the peak activated voxel in each cluster. Labels are given in AAL system (Automated Anatomical Labeling System) as implemented in SPM8.

In bilinguals, Portuguese, the L1, seems to exhibit more left-lateralized stable voxels in the frontal and parietal lobes, but more right-lateralized stable voxels in the temporal regions. In turn, results indicate that English, the L2, recruits more voxels, more areas of the brain than the L1. There are more stable voxels in left frontal areas, in the left precuneus (in the same coordinates from the stable area in Portuguese reading), and in the left fusiform. Reading in Portuguese and in English elicit stable voxels in the right superior parietal region (the same coordinates), a slightly bigger cluster for English (54 voxels, 51 for Portuguese). It seems that the L1 is engaging the traditional language network while the L2, the anterior attention network. As well, figures suggest that reading in English displays a more frontal representation than reading in Portuguese.

4.2.2 Stability analysis: differences in processing L1 in bilinguals and monolinguals

In the same manner as in the previous subsection, we examined the difference in representation location for Portuguese when bilinguals and monolinguals read sentences. Hit maps were generated with the most stable voxels, the ones that display a tuning curve, across all participants. Following Mason and Just (2015), it is believed that such voxels are consistently selective to the processing of Portuguese words in the context of sentences. Figure 4.19 and table 4.16 present the top stable voxels for monolinguals reading in Portuguese.

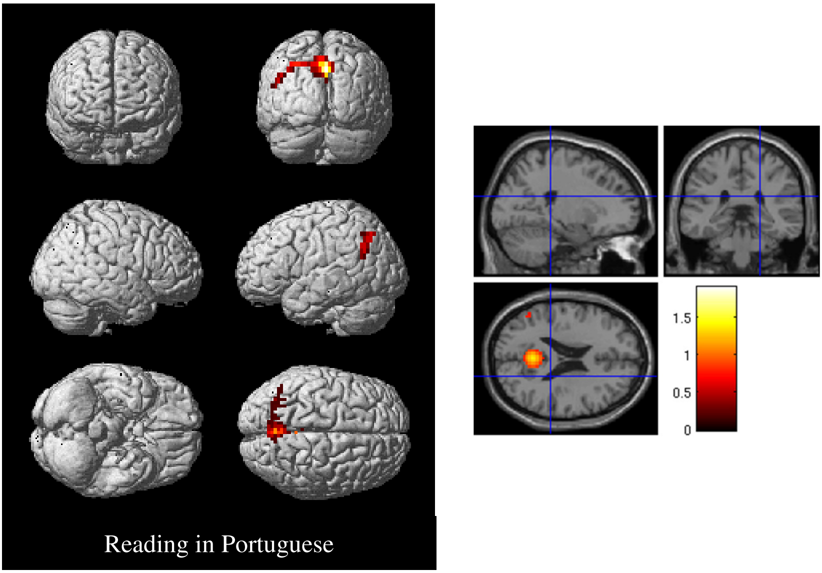


Figure 4.20. Rendered views of the most stable voxels for monolinguals reading in Portuguese (SPM8; smoothed data; height threshold = 0.75)

Table 4.16. Group stability for monolinguals reading in Portuguese

Top stable voxels in Portuguese reading					
Centroid and adjacent activation	Number of voxels	BA	MNI Coordinate		
			x	*y*	*z*
Parietal					
L precuneus	431	BA7/31	0.125	-58.875	34

Note: Clusters of stable voxels, smoothed, height threshold = 0.75. Group stability for monolinguals reading in Portuguese. Region labels apply to the entire extent of the cluster with peak maxima designated by first locale cited. MNI coordinates are for the peak activated voxel in each cluster. Labels are given in AAL system (Automated Anatomical Labeling System) as implemented in SPM8.

Interestingly, monolinguals display 431 stable voxels in the left precuneus in the same coordinates the bilinguals do. As shown in the previous subsection, bilinguals exhibit more stable voxels in predominantly left-lateralized frontal and parietal areas and mainly the right middle temporal region. Such an observation corroborates the inference presented in this work that bilinguals recruit more areas throughout the brain even when reading in their L1.

4.2.3 Word length and lexical frequency effects in bilinguals

Word length and lexical frequency effects were correlated with the difference between languages to inspect whether they may modulate the language difference. As regards the procedure, the language difference (Portuguese-English) was computed, the word images and their corresponding words were fit into a regression model for each participant and the slope of the regression (beta matrix) was saved for each participant (within-subject level). Then, all the participants' regression beta matrix was fit into a one-sample *t* test (between-subject level) to investigate whether the variables word length and lexical frequency have an effect on brain activation levels and how much each variable may explain the language difference. Concerning word length effects, figure 4.20 and table 4.17 display the results ($T = 1.81$, $p = .05$, uncorrected; no effect was found with a stricter threshold).

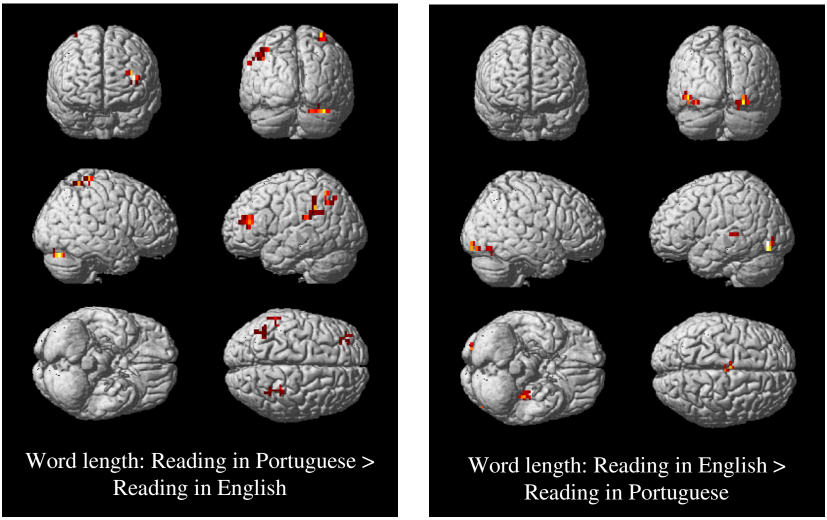


Figure 4.21. Brain views of the contrasts between reading in the two languages with the mean word length of the two languages. (SPM8; p = .05, uncorrected; T = 1.81; extent threshold voxels=15)

Table 4.17. Group labeling of activation for the difference between languages and word length

Contrast Portuguese-English and word length						
Centroid and adjacent activation	Cluster size (voxels)	*T* (12)	BA	MNI Coordinate		
				x	y	z
Frontal						
L dorsolateral prefrontal cortex	31	4.33	BA46	-37.375	38	16
Parietal						
L supramarginal	22	4.07	BA40	-53	-43.25	34
R postcentral	17	3.70	BA3	31.375	-33.875	70
L inferior parietal (IPS)	17	3.57	BA7	-34.25	-58.875	52
Occipital						
R fusiform	23	4.27	BA37	34.5	-74.5	-26

Contrast English-Portuguese and word length				
Centroid and adjacent activation	Cluster size (voxels)	*T* (12)	BA	MNI Coordinate

				x	y	z
Frontal						
L supplementary motor area	15	3.30	BA6	-3	-8.875	52
Temporal						
L fusiform	123	5.32	BA37	-28	-37	-8
L superior temporal	22	3.36	BA42	-43.625	-40.125	16
Occipital						
R inferior occipital	28	3.37	BA19	31.375	-93.25	-14

Note: Clusters of voxels significant at p <.05, uncorrected, T = 1.81, extent threshold = 15 voxels. Group contrasts of English-Portuguese and Portuguese-English reading with word length. Region labels apply to the entire extent of the cluster with peak maxima designated by first locale cited. T-values and MNI coordinates are for the peak activated voxel in each cluster. Labels are given in AAL system (Automated Anatomical Labeling System) as implemented in SPM8.

As already mentioned in the method section, Portuguese word length ranged from 3 to 11 letters (e.g.: *rua*, *restaurante*), with a mean of 6.79 (*SD* = 2.00), while English word length ranged from 3 to 10 letters (e.g.: *car*, *television*), with a mean of 5.66 (*SD* = 1.70). Despite such differences, our analysis revealed that the longer the words in Portuguese, participants display more activation in the left dorsolateral prefrontal cortex (DLPFC), right fusiform, left supramarginal, left IPS, and right postcentral areas. On the other hand, the longer the words in English, participants exhibit more activation in the left fusiform, right inferior occipital, left superior temporal and left supplementary motor area. The involvement of more visual areas in English may be due to the fact that English has a deep orthography, while Portuguese, a shallow one. Thus, reading longer words in English seems to require more visual areas than reading in Portuguese. It seems that these results are revealing effects of the phonological and lexical routes. As regards lexical frequency effects, figure 4.21 and table 4.18 present the results (T = 1.81, p <.05, uncorrected).

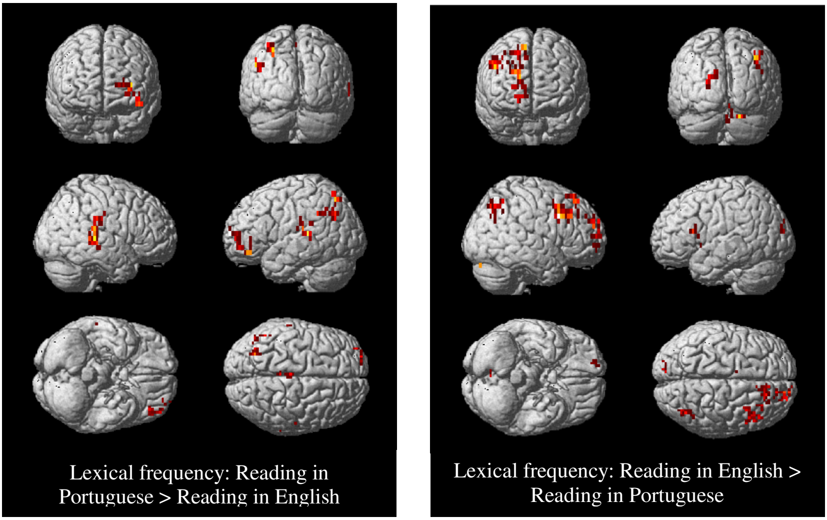


Figure 4.22. Brain views of the contrasts between reading in the two languages with the mean lexical frequency of the two languages (SPM8; p<.05, uncorrected; T=1.81; extent threshold voxels=15)

Table 4.18. Group labeling of activation for the difference between languages and lexical frequency

Contrast Portuguese-English and lexical frequency						
Centroid and adjacent activation	Cluster size (voxels)	*T* (12)	BA	MNI Coordinate		
				x	*y*	*z*
Frontal						
L superior frontal	17	3.21	BA10	-24.875	63	10
L orbitofrontal	16	3.09	BA11	-40.5	41.125	-14
Parietal						
L posterior cingulate	25	4.70	BA5	0.125	-37	46
L superior parietal	19	3.97	BA7	-28	-71.375	52
L angular	17	3.74	BA40	-46.75	-46.375	34
Temporal						
R superior temporal	48	3.94	BA22	59.5	-30.75	16
L superior temporal	23	4.30	BA42	-53	-33.875	10

Contrast English-Portuguese and lexical frequency

Centroid and adjacent activation	Cluster size (voxels)	*T* (12)	BA	MNI Coordinate		
				x	*y*	*z*
Frontal						
R middle frontal	73	4.20	BA9	43.875	13	34
R superior frontal	37	3.84	BA8	18.875	34.875	52
R superior frontal	33	5.16	BA10	15.75	56.75	22
R anterior cingulate	33	3.51	BA24	6.375	41.125	-2
L supplementary motor area	24	2.91	BA6	-6.125	-2.625	52
L inferior frontal (triangularis)	20	3.36	BA45	-40.5	19.25	16
Parietal						
R angular	25	3.27	BA7	40.75	-65.125	46
L posterior cingulate	16	3.80	BA19	-15.5	-52.625	10
Occipital						
L superior occipital	17	3.22	BA18	-18.625	-87	22
R fusiform	24	4.09	BA18	22	-83.875	-26

Note: Clusters of voxels significant at p <.05, uncorrected, T = 1.81, extent threshold = 15 voxels. Group contrasts of Portuguese-English and English-Portuguese reading with lexical frequency. Region labels apply to the entire extent of the cluster with peak maxima designated by first locale cited. *T*-values and MNI coordinates are for the peak activated voxel in each cluster. Labels are given in AAL system (Automated Anatomical Labeling System) as implemented in SPM8.

Results suggest that the more frequent the words in Portuguese, participants display more activation in the bilateral superior temporal, left superior parietal, posterior cingulate and angular regions as well as orbitofrontal and frontal superior areas. In contrast, the more frequent the words in English, participants exhibit more clusters of activation in right middle and superior frontal regions, left supplementary motor area (SMA) and IFG, right angular, left posterior cingulate and bilateral occipital visual areas, with focus on right fusiform. Reading more frequent words in the L1 seems to involve bilateral Wernicke's area and left-lateralized areas, while reading more frequent words in the L2, seems to engage more right-lateralized regions. The next sections brings the effects of such variables in monolinguals reading in Portuguese.

4.2.4 Word length and lexical frequency effects in monolinguals

As explained in the previous subsection, all the word images and their corresponding words were fit into a regression model for each participant and the beta matrix was saved for each participant. Then, all the participants' regression beta matrix was fit into a one-sample *t* test to investigate whether the variables word length and lexical frequency have an effect on brain activation levels in monolinguals reading in Portuguese. Concerning word length effects, figure 4.22 and table 4.19 display the results ($T = 1.86$, $p = .05$, uncorrected; no effect was found with a stricter threshold).

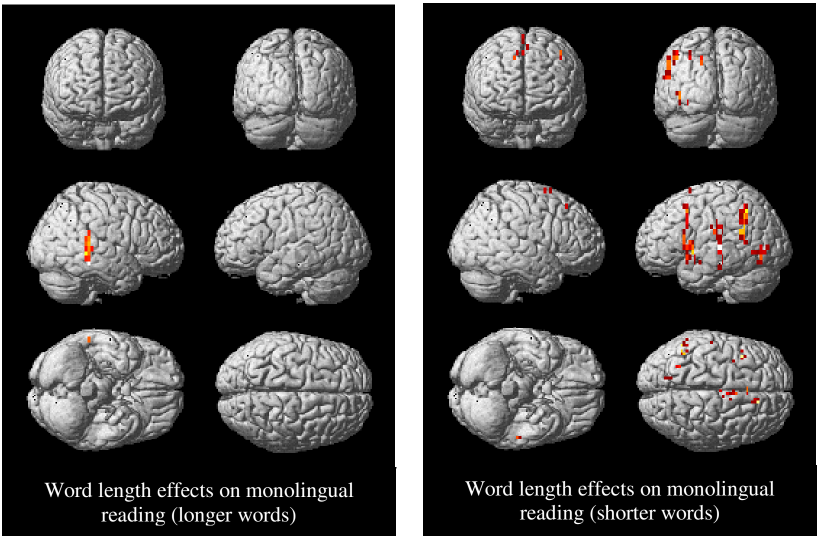


Figure 4.23. Brain views of the activation for monolingual reading in Portuguese and word length effects (SPM8; p=.05, uncorrected; T=1.86; extent threshold voxels=15)

Table 4.19. Group labeling of activation for monolingual reading in Portuguese and word length effects

Portuguese reading in monolinguals and word length effects (longer words)						
Centroid and adjacent activation	Cluster size (voxels)	*T* (10)	BA	MNI Coordinate		
				x	y	z
Temporal						
R superior temporal	15	3.18	BA22	59.5	-37	10

Portuguese reading in monolinguals and word length effects (shorter words)

Centroid and adjacent activation	Cluster size (voxels)	*T* (10)	BA	MNI Coordinate		
				x	y	z
Frontal						
L supplementary motor area	26	3.61	BA6	-3	0.5	52
L inferior frontal (opercularis)	23	4.07	BA44	-43.625	13	-8
R medial superior frontal	17	4.58	BA8	12.625	31.75	46
Parietal						
L superior parietal	18	3.13	BA7	-24.875	-74.5	52
Temporal						
L superior temporal	29	4.43	BA40	-53	-52.625	16
L superior temporal	18	6.93	BA22	-56.125	-24.5	4
Occipital						
L middle occipital	17	3.38	BA19	-31.125	-71.375	-2
Subcortical						
L insula	30	4.93		-37.375	-2.625	-8

Note: Clusters of voxels significant at p <.05, uncorrected, T = 1.86, extent threshold = 15 voxels. Group contrasts of monolinguals reading in Portuguese with word length. Region labels apply to the entire extent of the cluster with peak maxima designated by first locale cited. T-values and MNI coordinates are for the peak activated voxel in each cluster. Labels are given in AAL system (Automated Anatomical Labeling System) as implemented in SPM8.

Results suggest that the longer the words in Portuguese, monolinguals seem to recruit a small but significant cluster at the right superior temporal region. In turn, the shorter the words in Portuguese, monolinguals seem to recruit predominantly left-lateralized frontal areas, left superior temporal, subcortical, parietal and occipital regions. As regards lexical frequency effects, figure 4.23 and table 4.20 present the results (T = 1.86, p <.05).

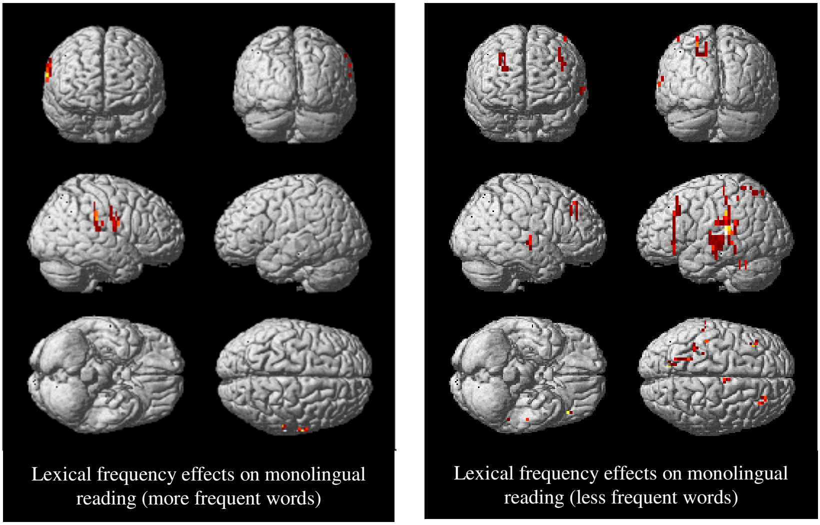


Figure 4.24. Brain views of the activation for monolingual reading in Portuguese and word length effects (SPM8; p=.05, uncorrected; T=1.86; extent threshold voxels=10)

Table 4.20. Group labeling of activation for monolingual reading in Portuguese and lexical frequency effects

Portuguese reading in monolinguals and lexical frequency effects (more frequent words)						
Centroid and adjacent activation	Cluster size (voxels)	*T* (10)	BA	MNI Coordinate		
				x	*y*	*z*
Parietal						
R supramarginal	14	3.54	BA40	65.75	-27.625	28
R supramarginal (postcentral)	12	3.56	BA40	65.75	-8.875	22

Portuguese reading in monolinguals and lexical frequency effects (less frequent words)						
Centroid and adjacent activation	Cluster size (voxels)	*T* (10)	BA	MNI Coordinate		
				x	*y*	*z*
Frontal						
L inferior frontal (orbitalis)	17	3.80	BA47	-43.625	28.625	-8

R middle frontal	10	3.21	BA9	25.125	38	40
R supplementary motor area	10	3.27	BA6	3.25	-2.625	64
Parietal						
L superior parietal	18	3.46	BA7	-18.625	-65.125	40
L inferior parietal (IPS)	11	2.81	BA7	-31.125	-43.25	46
L precuneus	10	5.00	BA7	-12.375	-52.625	34
Temporal						
L superior temporal	77	5.33	BA22	-65.5	-30.75	10
R superior temporal	10	2.94	BA22	50.125	-15.125	-2
Occipital						
L fusiform	10	4.26	BA37	-37.375	-52.625	-26

Note: Clusters of voxels significant at p <.05, uncorrected, T = 1.86, extent threshold = 10 voxels. Group contrasts of monolinguals reading in Portuguese with word length. Region labels apply to the entire extent of the cluster with peak maxima designated by first locale cited. T-values and MNI coordinates are for the peak activated voxel in each cluster. Labels are given in AAL system (Automated Anatomical Labeling System) as implemented in SPM8.

Findings reveal that the more frequent the words in Portuguese, our monolinguals display more activation in the right supramarginal region, traditionally implicated in reading. On the other hand, the less frequent the words in Portuguese, monolinguals exhibit more activation in the bilateral Wernicke's area, typically associated with comprehension. Monolinguals also display activation in left-lateralized parietal regions, bilateral frontal and left fusiform areas.

4.2.5 Semantic features and differences in the two languages

Our 42 features (see table 3.2 in the method chapter) were grouped into 9 categories (Abstraction, Animate Beings, Domain of Human Activity, Mental action/state, Physical action/state, Social action/state, Part of speech, Perceptual Characteristics and Time/Space). Voxels above threshold (p < .05, uncorrected, extent threshold = 5 voxels) were counted for each semantic feature, then grouped according to the categories. Brain areas are reported, in figure 4.24, as associative cortex and visual cortex to facilitate interpretation. In terms of associative cortex, the first and the second language activated similarly associative areas in the right hemisphere; in the left hemisphere, the L2 recruited more voxels than the L1. As regards visual cortex, the L1 made use of more voxels in the left hemisphere while the L2 recruited more voxels in the right hemisphere.

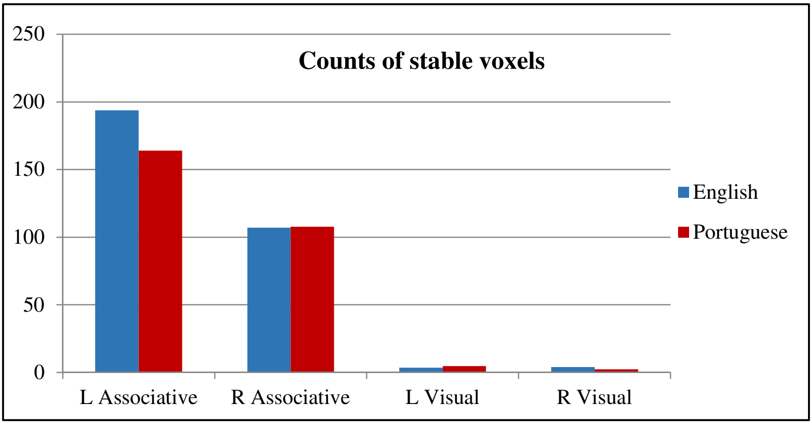
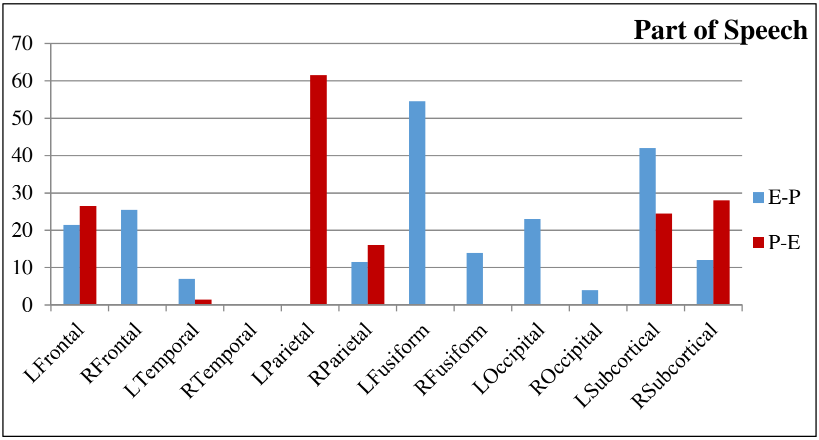
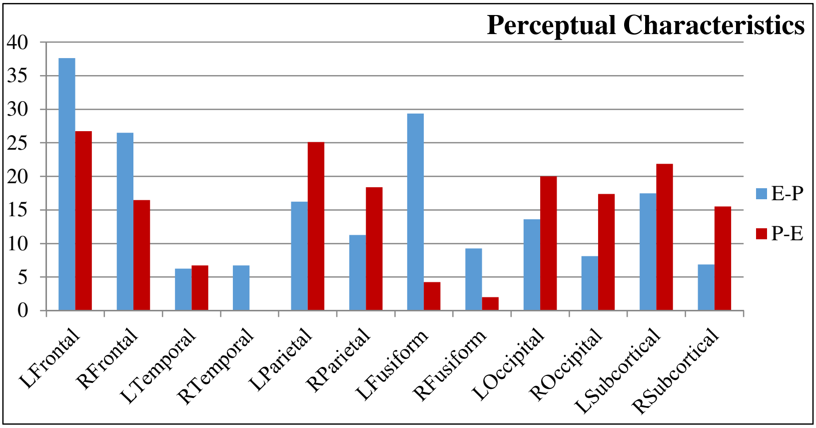
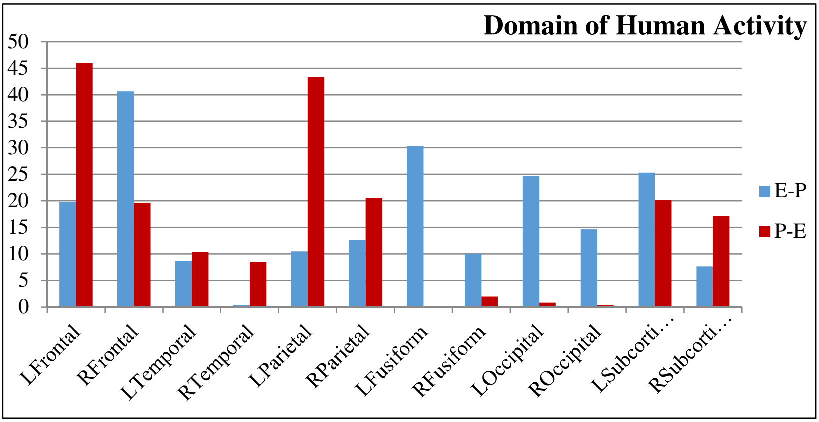


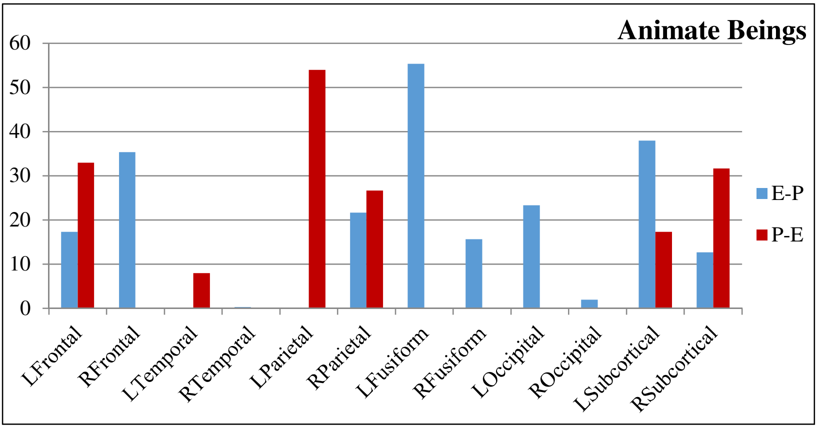
Figure 4.25. Counts of stable voxels ($p < .05$, uncorrected, extent threshold=5). The left associative cortex had 164 active voxels in Portuguese and 194, in English. The right associative cortex had 108 active voxels in Portuguese and 107, in English. The left visual cortex elicited 4.67 voxels in Portuguese and 3.5, in English. Finally, the right visual cortex elicited 2.42 voxels in Portuguese and 4, in English.

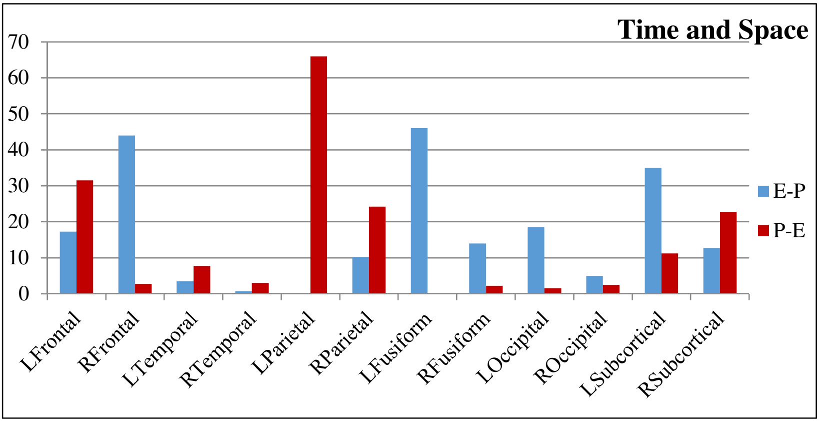
Graphs from figure 4.25 present the differences (English minus Portuguese and Portuguese minus English) in distribution of voxel counts across the brain and groups of semantic features. To facilitate understanding, we grouped brain areas as associative and visual areas in graphs 4.26. The graphs reveal that English is more dominant in left associative cortex for the Social and Physical action/state categories as well as Perceptual Characteristics. English seems to be more dominant in right associative cortex for Animate Beings, Time/Space, Part of Speech, and Domain of Human Activity groups; and in left visual areas for all feature groups. On the other hand, Portuguese is more dominant in left associative areas for all feature groups, and left visual areas are present, more significantly, in the Perceptual Characteristics group, and less significantly, in the Mental and Social Action/State groups. In the Time and Space group, a little number of voxels is recruited in the right visual cortex. Right association cortex areas are also activated during Portuguese reading but in an inferior number if compared to the left association cortex.

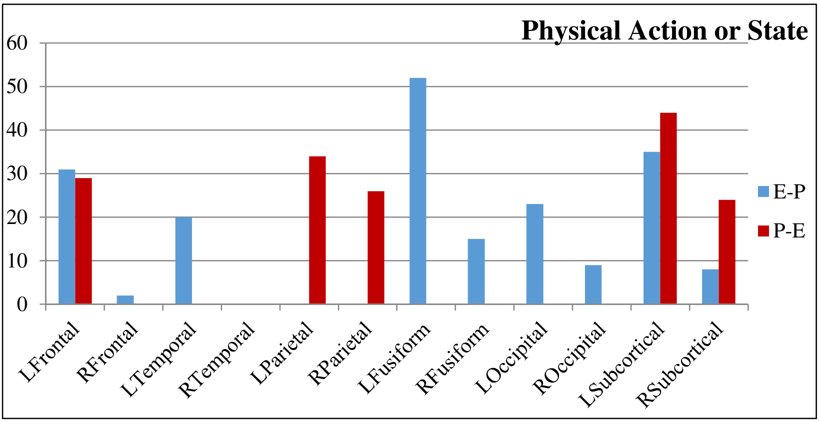

Part of Speech
70
60
50
40
30
20
10
0
LFrontal
RFrontal
LTemporal
RTemporal
LParietal
RParietal
LFusiform
RFusiform
LOccipital
ROccipital
LSubcortical
RSubcortical
E-P
P-E


Perceptual Characteristics
40
35
30
25
20
15
10
5
0
LFrontal
RFrontal
LTemporal
RTemporal
LParietal
RParietal
LFusiform
RFusiform
LOccipital
ROccipital
LSubcortical
RSubcortical
E-P
P-E


Domain of Human Activity
50
45
40
35
30
25
20
15
10
5
0
LFrontal
RFrontal
LTemporal
RTemporal
LParietal
RParietal
LFusiform
RFusiform
LOccipital
ROccipital
LSubcorti…
RSubcorti…
E-P
P-E


Animate Beings
60
50
40
30
20
10
0
LFrontal
RFrontal
LTemporal
RTemporal
LParietal
RParietal
LFusiform
RFusiform
LOccipital
ROccipital
LSubcortical
RSubcortical
E-P
P-E


Time and Space
70
60
50
40
30
20
10
0
LFrontal
RFrontal
LTemporal
RTemporal
LParietal
RParietal
LFusiform
RFusiform
LOccipital
ROccipital
LSubcortical
RSubcortical
E-P
P-E


Physical Action or State
60
50
40
30
20
10
0
LFrontal
RFrontal
LTemporal
RTemporal
LParietal
RParietal
LFusiform
RFusiform
LOccipital
ROccipital
LSubcortical
RSubcortical
E-P
P-E

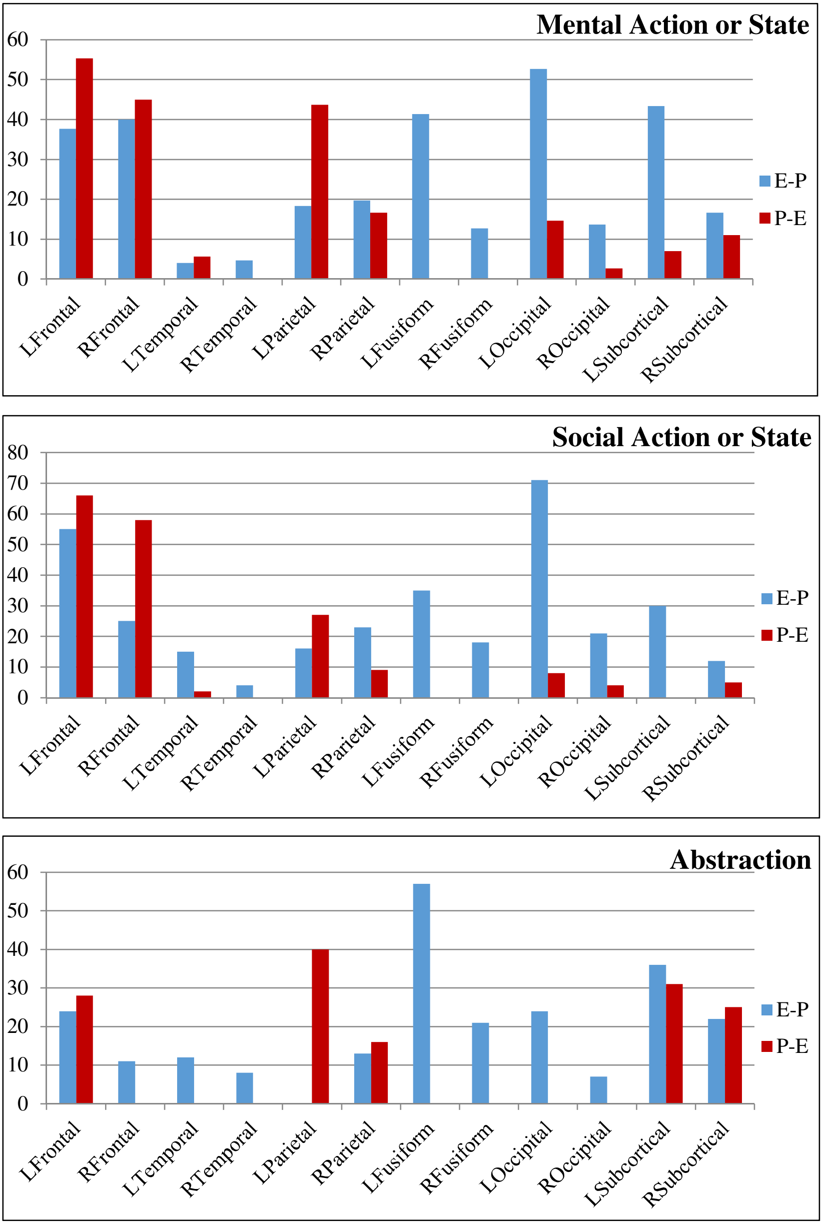
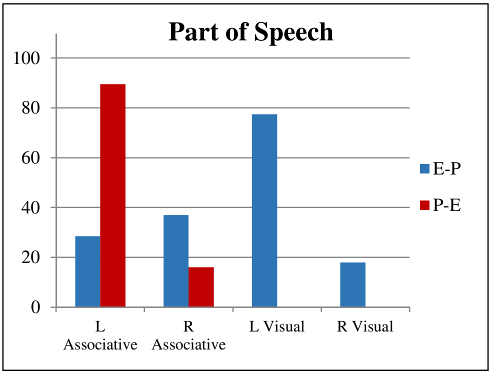
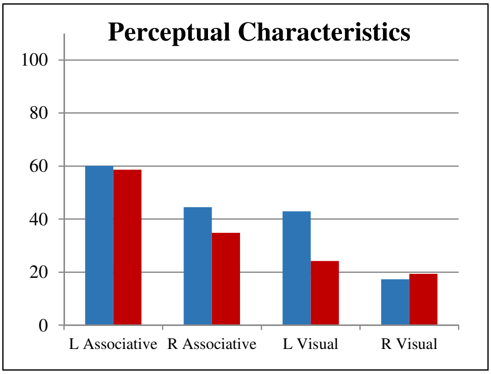
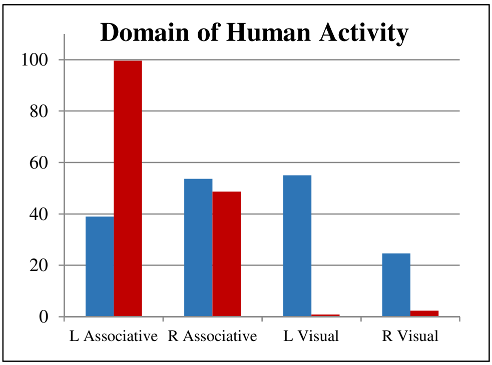
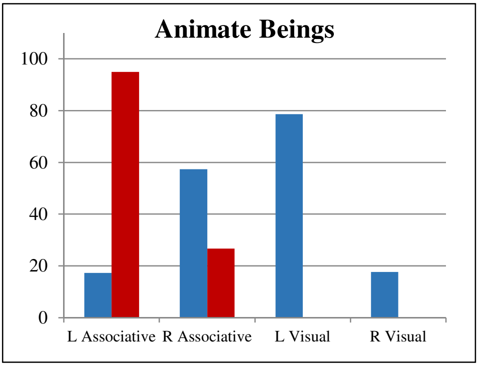


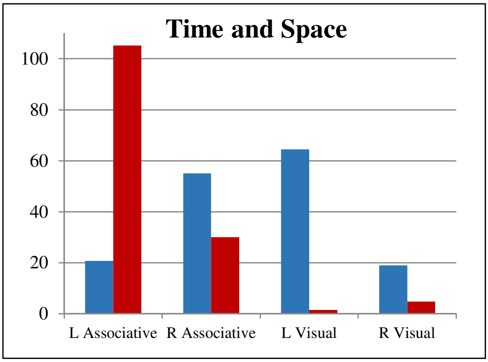
Figure 4.26. Language difference, English minus Portuguese (blue bars) and Portuguese minus English (red bars) in distribution of voxel counts across the brain and groups of semantic features ($p < .05$, uncorrected, extent threshold=5).

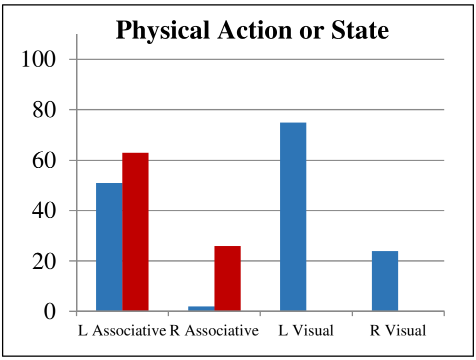

Part of Speech
100
80
60
40
20
0
L Associative
R Associative
L Visual
R Visual
E-P
P-E


Perceptual Characteristics
100
80
60
40
20
0
L Associative
R Associative
L Visual
R Visual


Domain of Human Activity
100
80
60
40
20
0
L Associative
R Associative
L Visual
R Visual


Animate Beings
100
80
60
40
20
0
L Associative
R Associative
L Visual
R Visual


Time and Space
100
80
60
40
20
0
L Associative
R Associative
L Visual
R Visual


Physical Action or State
100
80
60
40
20
0
L Associative
R Associative
L Visual
R Visual

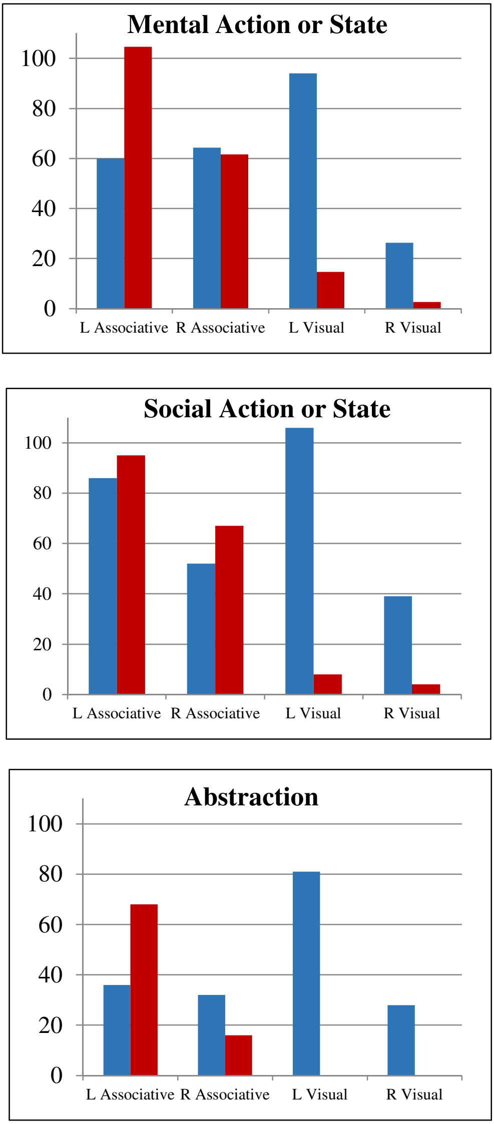


Figure 4.27. Language difference, English minus Portuguese (blue bars) and Portuguese minus English (red bars) in distribution of voxel counts across associative and visual areas of the brain and groups of semantic features ($p < .05$, uncorrected, extent threshold=5).

When reading sentences such as "The woman left the restaurant after the storm/*A mulher saiu do restaurante depois da tempestade*" and "The wealthy couple left the theater/*O casal rico saiu do teatro*", bilinguals activate more right associative areas and left visual areas for Animate Beings (woman, couple) and Time/Space (left, restaurant, after the storm, theater) when reading in English. When reading in Portuguese, they activate only left associative areas instead. Portuguese reading presented visual area activation only when participants read words related to Perceptual Characteristics, in sentences such as "The school was famous/*A escola era famosa*" and "The girl saw the small bird/*A garota viu o passarinho*" (famous, small). Altogether, our results suggest that the L2 recruits more right-lateralized brain areas than the L1, that the bilingual brain makes use of more cortical tissue when processing the L2.

4.3 SEMANTIC NEURAL REPRESENTATION IDENTIFICATION

This section reports the results, conducted with multi-voxel pattern analysis and machine learning techniques, about the decoding of sentence representation within-language (training and testing in Portuguese data or training and testing in English data) and cross-language (training in Portuguese data and testing in English data and training in English data and testing in Portuguese data).

4.3.1 Within-language classification

In this subsection, the results for the within-language classification: training and testing in Portuguese for bilinguals and monolinguals, and training and testing in English for bilinguals are presented. With bilinguals, we used basically two methods: GNB (a generative classifier) and sentence reconstruction methods. The GNB classifier uses the training data to estimate the probability distribution over sentence presentations. For sentence reconstruction, 60 leave-one-out classifications were conducted. A word image in the training set, for instance "mob", was generated by averaging all the sentence mean percent signal change (MPSC) images containing this particular word. We averaged sentences such as "The mayor negotiated with the mob" and "The reporter spoke to the loud mob" assuming that the signals related to semantic features of other words canceled each other out while the signals related to the semantic features of "mob" were strengthened. Within each classification fold, we computed the signal stability of word images over multiple presentations and selected the 300 most stable voxels from the pre-determined 39 meta-language cuboids (as explained in the Method chapter). The MPSC signals of these selected voxels in the training set were regressed against the CCBI semantic features and case role features. This trained model was used to generate the predicted word images. Then, the word images were added linearly to 'compose' the predicted sentence images. Figure 4.27 illustrates the procedure to decode sentences within-language.

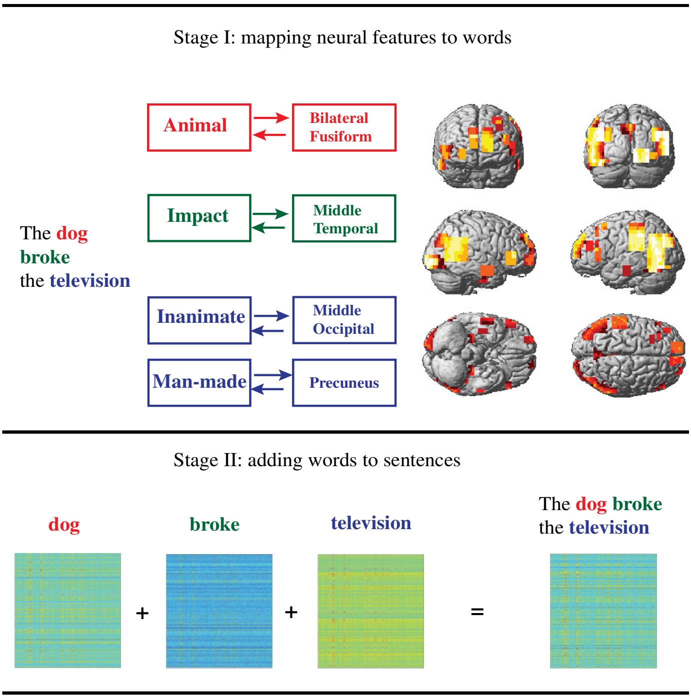


Figure 4.28. Illustration of the neural computation principles. Upper row: each word is associated with a set of semantic features and with brain locations. By establishing the link between the semantic features and modulations of these locations, word images could be predicted. Lower row: by linear adding the predicted images of the content words, the predicted image of the *sentence gist* could be constructed.

Finally, the Euclidean distances between the left-out true sentence image and all the sixty predicted images were computed, in order to rank order all the predictions by the similarity to the true sentence image. The rank accuracy was computed as the normalized rank of the correct target sentence in the lists of candidate sentences. Table 4.21 presents the accuracy results of our 12 bilinguals.

Table 4.21. Individual accuracies, group mean, and best accuracy of bilinguals, training and testing in Portuguese (left side), and training and testing in English (right side)

BILINGUALS										
Training & testing in P	**SR with case role (top voxels)**	**SR (39 cubes)**	**SR with case role (39 cubes)**	**GNB**		**Training & testing in E**	**SR with case role (top voxels)**	**SR (39 cubes)**	**SR with case role (39 cubes)**	**GNB**
B P1	0.620	0.604	0.661	0.603		B P1	0.689	0.582	0.668	0.561
B P2	0.616	0.615	0.591	0.554		B P2	0.739	0.673	0.763	0.646
B P3	0.581	0.576	0.629	0.566		B P3	0.547	0.540	0.569	0.516
B P4	0.650	0.622	0.629	0.607		B P4	0.738	0.668	0.712	0.719
B P5	0.541	0.543	0.526	0.506		B P5	0.632	0.632	0.651	0.544
B P6	0.729	0.676	0.695	0.670		B P6	0.712	0.716	0.699	0.704
B P7	0.619	0.587	0.633	0.587		B P7	0.795	0.740	0.791	0.665
B P8	0.553	0.473	0.538	0.539		B P8	0.561	0.540	0.525	0.524
B P9	0.808	0.718	0.757	0.647		B P9	0.578	0.584	0.607	0.662
B P10	0.582	0.605	0.595	0.596		B P10	0.727	0.691	0.718	0.628
B P11	0.725	0.688	0.723	0.647		B P11	0.629	0.612	0.608	0.569
B P12	0.583	0.500	0.535	0.579		B P12	0.675	0.611	0.669	0.570
M	0.634	0.601	0.626	0.592		*M*	0.668	0.632	0.665	0.609
SD	0.077	0.069	0.071	0.045		*SD*	0.079	0.066	0.078	0.070
Best	0.808	0.718	0.757	0.670		*Best*	0.795	0.740	0.791	0.719

Note: P stands for Portuguese and E for English; SR for sentence reconstruction; GNB, for Gaussian naïve Bayes classifier; M for mean; and SD for standard deviation.

Data reveals that the GNB classifier yields the poorest accuracies for both languages (mean of 59.2% for Portuguese and 60.9% for English). The best accuracy results come from sentence reconstruction analysis with case role (with either top voxels or the 39 cubes). Such results were expected since the algorithms could learn essential characteristics from the training data taking into account semantic and case role features. By top voxels, it is meant the top stable voxels as shown in a previous section; and by 39 cubes, the cubes derived from data collected with three independent monolingual English-speaking participants reading 240 sentences (as presented in the method section). As regards the classification accuracies for monolinguals, table 4.22 presents the accuracies for 9 of our 10 monolinguals (one participant's set of data could not be used for classification) with the method that produced the best results: sentence reconstruction. Monolingual accuracies (mean of 66.4%) are higher than the accuracies of bilinguals reading in Portuguese (63.4%). Rank accuracies are above chance (rank accuracy >=56%, p = < .05), except for P3's accuracy that falls behind.

Table 4.22. Individual accuracies, group mean, and best accuracy of monolinguals, training and testing in Portuguese

MONOLINGUALS	
Training & testing in Portuguese	**SR with case role (39 cubes)**
M P1	0.750
M P2	0.580
M P3	0.480
M P4	0.774
M P5	0.758
M P6	0.607
M P7	0.736
M P8	0.622
M P9	0.671
Mean	0.664
Standard deviation	0.099
Best	0.758

Note: We chose to report only the sentence reconstruction accuracies with case role and the 39 metalanguage cuboids because this method yields the best accuracies for all participants.

For the between-subject sentence prediction, the same procedures were followed, except that one subject was left out as the testing subject and all the rest served as training subjects. Within each classification fold, the signals of testing sentence in the training subjects were also held out and not used for training the regression algorithm, such that the procedure was not contaminated by the algorithm 'knowing' the test sentence in the training subjects. We ran between-subject prediction only for Portuguese to investigate Portuguese-sentence prediction using neurosemantic locations derived from English. From our 22 Brazilian Portuguese speakers (12 bilinguals and 10 monolinguals), we conducted the analysis with the data of eight bilinguals and 7 monolinguals (total of 15 participants). Figure 4.28 illustrates the rank accuracy of each participant being the test subject while all the other participants' data were used as training data. Participants' accuracies reached significance (rank accuracy ≥ 56%, p <.05). As a group, the mean accuracy is 63.6% (SD = 4.5%).

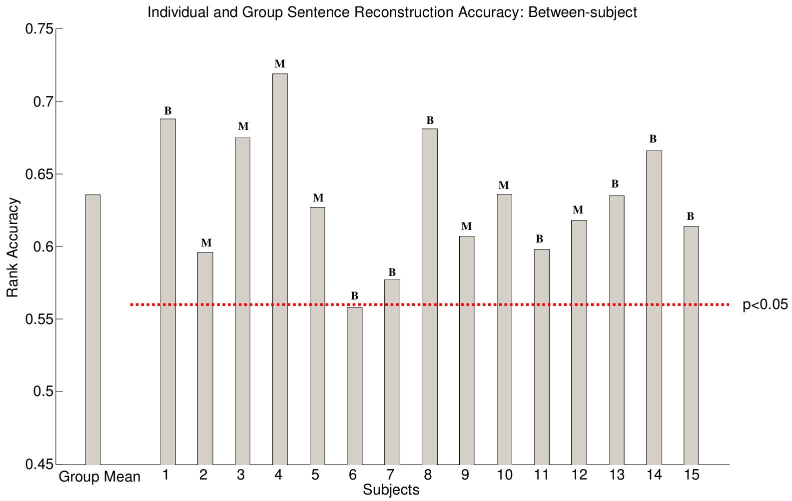


Figure 4.29. Between-subject sentence prediction mean rank accuracies of individual participants and the group mean, training on voxels from meta-language cuboids using a generative regression model by CCBI semantic features and case role features. The red dashed line indicated the chance level determined by a Monte Carlo simulation of 5,000 permutations.

To verify that the generative model made predictions systematically on the gist of each sentence and not on idiosyncrasies of other factors such as phonological similarities or familiarities, the top five ranked sentences from a subset of perfectly predicted sentences (rank accuracy = 1) were analyzed, and some examples were shown in figure 4.29.

Stimulus sentence: Os pais visitaram a escola. (The parent visited the school.)

Human group, Social, Location

Top 5 Model Predictions (translated to English)

Rank:
1. The parent visited the school.
2. The politician visited the family.
3. The happy couple visited the embassy.
4. The parent bought the magazine.
5. The family was happy.

Stimulus sentence: O diplomata negociou na embaixada. (The diplomat negotiated at the embassy.)

Political Government, Communication,

Top 5 Model Predictions (translated to English)

Rank:
1. The diplomat negotiated in the embassy.
2. The witness shouted at the trial.
3. The mayor negotiated with the mob.
4. The old doctor walked through the hospital
5. The scientist watched the duck.

Stimulus sentence: O cachorro quebrou a televisão. (The dog broke the television.)

Animate, Physical, Negative Valence

Top 5 Model Predictions (translated to English)

Rank:
1. The dog broke the television.
2. The author kicked the desk.
3. The young girl played soccer.
4. The child broke the glass in the restaurant.
5. The mob was dangerous.

Stimulus sentence: A flor era amarela. (The flower was yellow.)

Adjective, Color, Appearance

Top 5 Model Predictions (translated to English)

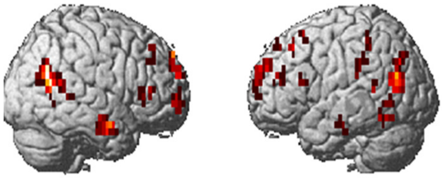
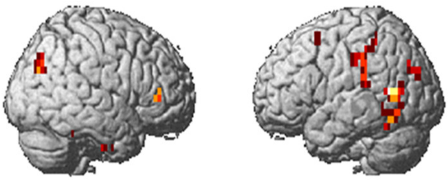
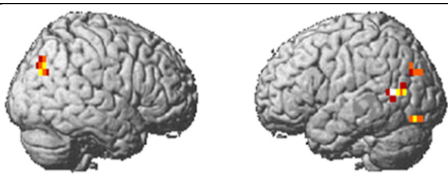
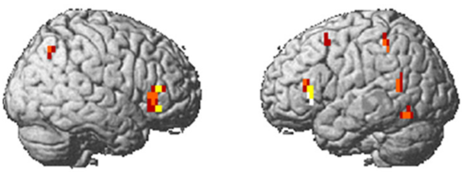
Rank:
1. The flower was yellow.
2. The magazine was yellow
3. The street was dark.
4. The street was empty at night.
5. The yellow bird flew over the field.

Figure 4.30. The top five ranked sentences from the generative model in a subset of perfectly predicted sentences.

The prediction algorithm not only 'guessed' the target sentence correctly by putting it at the top, but also ranked the following runners-up systematically. These runners-up came from the same semantic cohort of the target, defined by semantic features in the black rectangle. Such systematic runners-up cohort pattern indicates that the generative model grasped the gist of the target stimulus sentence.

It is relevant to highlight that the generative model described above is based on human-interpretable semantic features. By adding the 42 semantic features in the regression model, it is hypothesized that they are the key modulators of the neural activity variances for meaning processing in the context of sentences. As well, by adding the neurosemantic cuboids (derived from three English monolingual readers), the model seems to be able to predict sentences in Portuguese speakers (monolinguals and bilinguals), thus, indicating that these locations may constitute a language-independent concept network. The organization of these locations present an internal structure, resulted from factor analyses. Each semantic factor was defined by the location cohort, size and weight loadings. Table 4.23 presents the factors and the locations according to the data analyzed. For example, the biggest location cohort was devoted to "social interaction", involving 13 locations (bilateral precuneus, bilateral middle temporal lobe, bilateral superior frontal areas, and superior medial frontal and superior orbital frontal areas in the right hemisphere). The "action" cohort involves seven clusters (in the left middle and inferior temporal areas, left supramarginal, left inferior frontal gyrus, as well as the right angular gyrus and fusiform). "Shelter" involves bilateral parahippocampal areas, bilateral precuneus, and bilateral middle occipital areas.

Table 4.23. The neurosemantic factors and their locations

Factor	Label	Associated Semantic Features	Location in the brain
1	Social Interaction	Communication Knowledge Person Social Political/Government Law Human-group	
2	Well-being	Health Money	
3	Action	Impact Change of location Physical action Inanimate Fighter Change of physical state	
4	Shelter	Setting Shelter Unenclosed Man-made	
5	Eating	Eating/drinking	
6	Natural perception	Color Natural	

Such findings may indicate that common factors critical to human life across cultures might be encoded in common neural areas. Though these factors may be grounded in different languages subsequently, prediction algorithms could by-pass the language difference by extracting neural activities within these areas. Now, let us turn to the next subsection about the cross-language classification results.

4.3.2 Cross-language classification

Cross-language decoding was achieved by employing common *semantic features* and by finding common neural features (active locations) such that a mapping is established. Extracted neural features from the 39 meta-language cuboids were modeled on the semantic features, such that a direct relationship between them could be established, which is the foundation for cross-language classification. Figure 4.30 recaps the scheme for cross-language decoding.

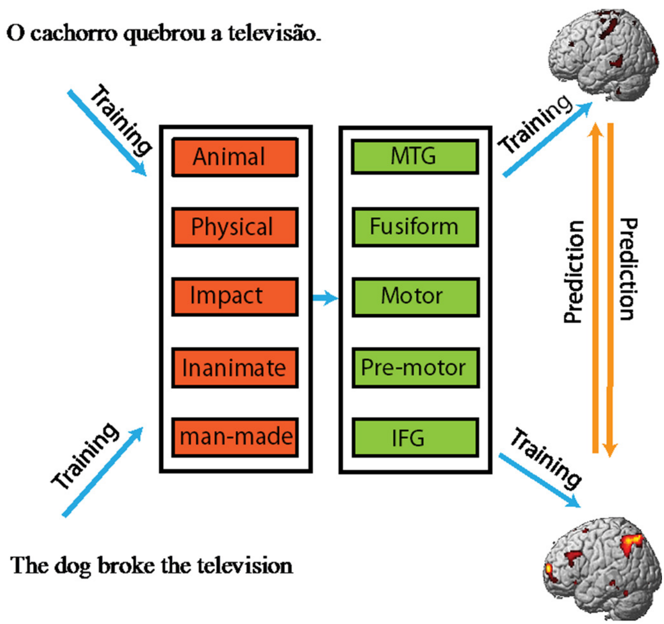


Figure 4.31. The general scheme for cross-language decoding (as presented in the Method chapter)

We used five methods to extract neural features of the two different languages to find a common neural space between these languages. Within each classification fold, common neural features were selected based on canonical correlation analysis (CCA) and four other methods based on voxel stability. CCA assumes that linear combinations of voxel sets can be found, such that these combinations in one language can be projected on the other (for more details, see the method section). In turn, stability is the pairwise correlations of word images across presentations. We computed stability in four direct ways: (1) overall stability (both training and testing language); (2) cross-language stability (paired presentations from different languages and correlation); (3) separate stability (paired presentations within each language, combination of most stable voxels); and (4) within-language stability of the training language (the test language was not involved; only the stability of the training set of the training language). Table 4.24 presents the accuracies at the individual and group level for the five methods of voxel selection in cross-language classification (training in English, testing in Portuguese; and training in Portuguese, testing in English).

Table 4.24. Individual mean, group mean, group best and best 8 participants' rank accuracies for the five kinds of voxel selection methods in both prediction directions (E to P and P to E)

BILINGUALS											
	Training in English, testing in Portuguese						**Training in Portuguese, testing in English**				
	CCA	**Overall Stability**	**Cross Stability**	**Separate Stability**	**Training language only**		**CCA**	**Overall Stability**	**Cross Stability**	**Separate Stability**	**Training language only**
P1*	0.558	0.670	0.639	0.628	0.629		0.609	0.661	0.661	0.641	0.594
P2*	0.699	0.662	0.676	0.652	0.649		0.605	0.661	0.647	0.605	0.634
P3	0.607	0.596	0.590	0.545	0.559		0.613	0.551	0.541	0.580	0.554
P4*	0.792	0.680	0.683	0.642	0.650		0.673	0.712	0.703	0.664	0.666
P5	0.633	0.620	0.592	0.571	0.556		0.554	0.563	0.572	0.555	0.556
P6*	0.709	0.696	0.675	0.641	0.654		0.738	0.678	0.659	0.680	0.659
P7*	0.723	0.661	0.670	0.618	0.635		0.691	0.673	0.697	0.610	0.619
P8	0.575	0.558	0.528	0.496	0.509		0.623	0.549	0.559	0.561	0.520
P9*	0.695	0.626	0.607	0.640	0.622		0.718	0.683	0.675	0.711	0.678
P10*	0.681	0.651	0.617	0.636	0.638		0.630	0.646	0.660	0.579	0.615
P11*	0.652	0.656	0.635	0.569	0.578		0.744	0.645	0.660	0.665	0.630

P12	0.659	0.583	0.568	0.599	0.558		0.562	0.568	0.581	0.566	0.595
Mean Total	0.665	0.638	0.623	0.603	0.603		0.647	0.633	0.635	0.618	0.610
SD	0.066	0.042	0.049	0.047	0.048		0.065	0.058	0.056	0.053	0.049
Mean Best 8	0.689	0.663	0.650	0.628	0.632		0.676	0.670	0.670	0.644	0.637
SD	0.066	0.021	0.029	0.025	0.024		0.056	0.045	0.020	0.041	0.029
Best	0.792	0.696	0.683	0.652	0.654		0.744	0.712	0.703	0.711	0.678

Note: A star beside the participant number means that this participant is among the eight best subjects in cross-language accuracy.

Comparing the two prediction directions, one can notice that the rank accuracies of English to Portuguese prediction are generally higher than Portuguese to English prediction, though the trend is not significant. This 'small' difference might be due to the higher level and more distinct patterns of activation in the neural data of the L2 than the L1. As it is possible to note in the table, we selected the best eight participants (with stars) to conduct the analysis that follows. As a whole, CCA seems to be more advantageous in both directions compared to the other four stability-based methods. We also generated graphs to illustrate the rank accuracies in each direction of prediction for all five methods. On the next page, figure 4.31 shows the rank accuracies for training in English and testing in Portuguese, and figure 4.32, the accuracies for training in Portuguese and testing in English.

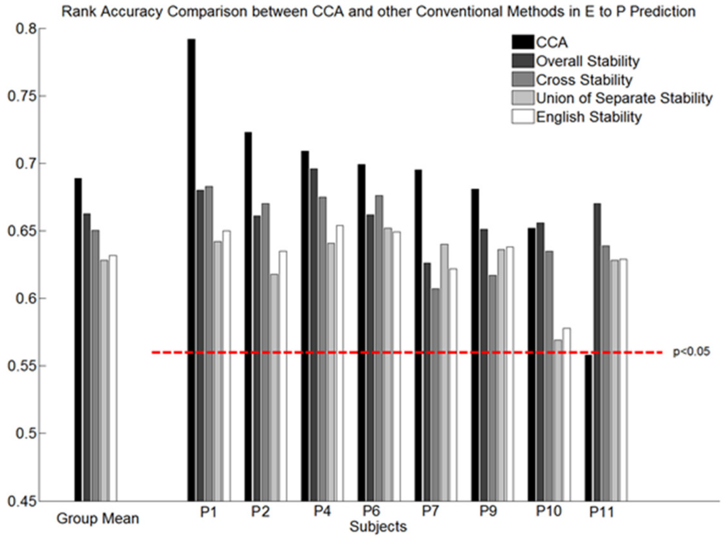


Figure 4.32. Cross-language sentence reconstruction results, training in English and predicting in Portuguese. The training data comes from the training language only. However, the voxel selection was based on either CCA or one of the four stability-based methods described above.

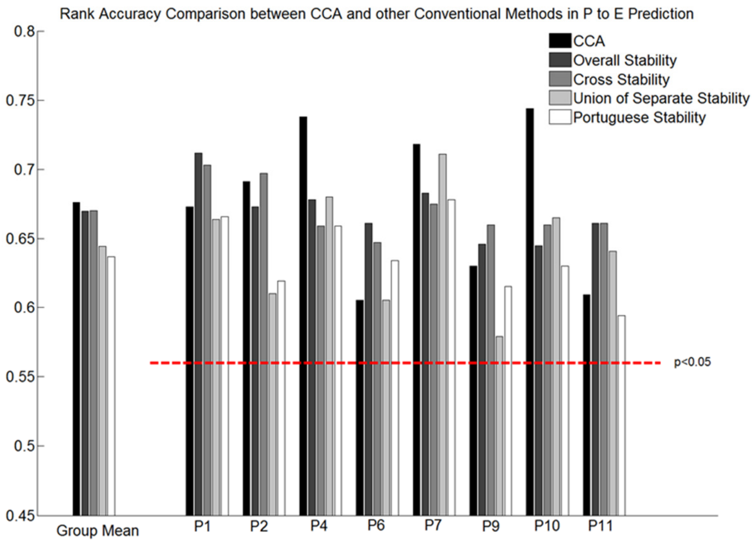


Figure 4.33. Cross-language sentence reconstruction results, training in Portuguese and predicting in English. The training data comes from the training

language only. However, the voxel selection was based on either CCA or one of the four stability-based methods described above.

In the English to Portuguese direction, one-way ANOVA indicated that the rank accuracies among the five methods were significant ($F(4,35) = 3.48$, p=.02). However, posthoc test using *Scheffe* test did not show any significance, though all the comparisons were marginally significant (p value ranges from .057 to .11), indicating that the rank accuracy changes are gradual. On the other hand, in the Portuguese to English direction, one-way ANOVA did not show significant differences among the five methods.

Going back to the English to Portuguese direction, the CCA method showed advantages for all but one participant (P8). Such a striking result was further explored and findings reveal that the actual overall stability scores could explain a very large portion of the variances of CCA accuracies (R^2=0.83). Breaking down the overall stability to cross-language stability and within language stability, it was found that most of the variances were explained by training language raw stability scores (R^2=0.81). Fitting the training language stability and the rank accuracy into a regression model resulted in a highly significant positive relationship, ($F(6) = 26.5$, $p = .002$). However, the raw stability scores could not explain the variances of the rank accuracies of the other stability-based methods. Figure 4.33 reveals that the underlying reason for this discrepancy is that 290 CCA components were constructed from more than 290 voxels. By assigning weights to many more voxels and linearly combining them, CCA components essentially 'resample' the voxels parametrically, i.e., they make use of 'semi-stable' voxels. This is advantageous when the voxel population is largely 'stable' (a lot of voxels' PSC signals are consistent across presentations). However, when only the top voxels are stable, CCA is not advantageous. The other stability-based methods only picked the top most stable voxels and were more robust to the overall change of raw stability scores.

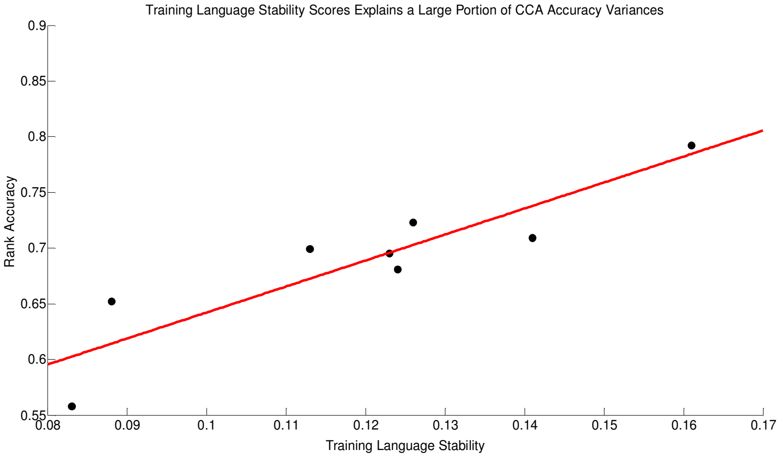


Figure 4.34. Raw training language stability could explain the variances in cross-language accuracies of CCA.

All in all, findings suggest that the commonalities in concept representations across languages are sufficient to allow the decoding of sentences across languages. This commonality was modeled at the word level through sentence reconstruction (linear addition). The following chapter presents the discussion of all the data reported in the present chapter in light of the literature.

CHAPTER 5
DISCUSSION

Everything we hear is an opinion, not a fact.
Everything we see is a perspective, not the truth.
(Marcus Aurelius)[41]

The present chapter aims at discussing the results presented in Chapter 4 in the light of the literature and the hypotheses posed for this study. It is divided according to the research questions posed in Chapter 3. First, the results concerning the representation and processing of L1 and L2 in the bilingual brain are discussed, followed by the representation and processing of L1 in the monolingual brain. The identification of the semantic neural representation of words in the context of sentences is discussed in the third section, followed by the effect of individual differences, namely L2 proficiency and working memory capacity, on bilingual and monolingual brain activation. Last but not least, the fifth section examines the effect of word length and lexical frequency on the brain activation of bilinguals and monolinguals.

5.1 RQ1: THE REPRESENTATION AND PROCESSING OF L1 AND L2 IN THE BILINGUAL BRAIN

Before discussing the results presented in the previous chapter, I would like to discuss some essential concepts for this study and provide a brief contextualization. By processing, I mean the processes that take place online while participants read the sentences silently inside the scanner. In turn, representation is what becomes activated through our thoughts, the perception and comprehension of words and sentences. As explained by Lindquist (2015, personal communication), brain representation is the physical basis for a mental experience or information structure. Thus, in this study, we attempted to elucidate the representation of L1 and L2 in the bilingual brain, and of the L1 in monolinguals. As well, we sought to understand the processes that take place in the brain while our participants were thinking about the

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[41]The quote is a paraphrase from the original "Remember that all is opinion". It is in the book named The Meditations written by Marcus Aurelius and translated to English by George Long, available online at <http://classics.mit.edu/Antoninus/meditations.2.two.html>. The paraphrase can be found at <http://www.spiritsite.com/writing/maraur/>.

meaning of the sentences they were presented with. Our study stands at the microstructure level of text comprehension (Kintsch & van Dijk, 1978) and the literal level of comprehension (Gagné et al., 1993). Our sentences encompass simple, concrete, literal and culturally nonspecific contents as well as basic level concepts (Rosch et al., 1976) such as *car*, *school*, and *flower*. Our approach focused on semantic composition, since individuals activate features of concepts while processing sentences. It is believed that people evoke visual images, past experiences, feelings and sounds as soon as they encounter the phrases on the screen. To illustrate, I remember asking a participant in the debriefing interview about the specific way she thought about the sentences, she mentioned that she found interesting the way she thought about the concepts *school* and *university*. When she encountered the first, the image "that appeared" in her mind was of the elementary school she studied at in Brazil. In turn, when thinking about *university*, the image that came to her mind was of the university she was studying at in Pittsburgh for less than a year. It was striking to her not evoking the image of her university in Brazil. As well, participants reported that the word *family* evoked good feelings and visual images related to being with their families.

Our bilingual participants follow the definition put forward by Grosjean (2012) that bilinguals are those who use two or more languages in their everyday lives. Following the commonsensical definition, our monolinguals know and use one language in their everyday lives. Some studies in the bilingual literature control for proficiency with self-ratings and questionnaires (subjective fluency) (Illes et al., 1999; Buchweitz, 2006; Yang et al., 2011, to mention a few). Other studies controlled for proficiency with objective fluency measures as standardized tests (Nakada et al., 2001; Crinion et al., 2006; Hernandez et al., 2015). In addition, as mentioned in the literature review, there are studies that did not control for proficiency at all (Kim et al., 1997; Marian et al., 2003). This study belongs to the group that applied an adapted part of a standardized test (TOEFL) to ensure, to some extent, a homogeneous group in terms of proficiency. In terms of age of acquisition, our participants are late bilinguals (mean AoA = 12.9) and use their languages on a daily basis.

Additionally, as recommended by Grosjean (1998), our participants were in a monolingual mode when they were tested. They were scanned in each language on separate days. To guarantee a monolingual mode in the language required for that specific day, I put the participants in a *language set* (Grosjean, 1998). I talked to them in

Portuguese when it was a Portuguese scanning day and in English when it was an English scanning day. It is crucial to emphasize that bilinguals are understood, in the present study, as integrated wholes who cannot be decomposed into two separate language parts (Grosjean, 2012). Bilinguals are not seen in this study as the sum of two monolinguals, instead, I follow Grosjean (2012) when he claims that bilinguals have "a unique and specific linguistic configuration" (p.75). I additionally argue for Bialystok and colleagues' (2012) position that bilingualism "imposes demands on the cognitive system that require brain regions not typically used for language processing" (p.245). Studies on bilingualism have attempted to provide answers to questions related to the issue of a shared system vs. two memory stores for the representation of concepts (Dufour & Kroll, 1995; Bialystok et al., 2009), as well as questions related to the extent bilinguals activate common cortical areas when processing their L1 and their L2 (Paradis, 2004). This issue will be considered in the third section of this chapter, where the semantic neural representation identification results are discussed.

In the present section, I discuss the bilingual results reached by sentence- and word-level analyses: reading > fixation, language difference, stability and semantic features analyses. At the sentence level, contrasted to fixation, reading in Portuguese engages a set of areas in the left inferior frontal gyrus (IFG) (901 voxels at $T = 6.76$, $p <.001$) with centroids peaking in the *pars opercularis* (BA44) and *pars triangularis* (BA45). The latter is normally implicated in semantic processing (Sirigu et al., 1998; Newman et al., 2003) and semantic access (Dehaene, 2009), while the former is traditionally associated with phonological and syntactical processing (Newman et al., 2003; Dehaene, 2009). Left supplementary motor area (SMA), the precentral region bilaterally (total of 393 voxels at mean $T = 5.59$, $p <.001$) with larger clusters in the left hemisphere, the right superior frontal sulcus extending to the putamen and caudate ($T = 6.01$, $p <.001$), and the left middle frontal area (27 voxels at $T = 5.58$, $p <.001$) are also recruited. Such areas may be involved in silent reading motor procedures (Jobard et al., 2011), in a rehearsal process "that refreshes the contents of WM" (Cabeza & Nyberg, 2000, p.19). Gitelman and colleagues (2005) claim that SMA activity is found in word-level orthographic, phonologic and semantic decision tasks. The SMA is typically associated with articulatory processes during comprehension. In this study, we assume that the SMA and adjacent regions were recruited for the comprehension of written sentences, reflecting silent articulatory processes. The caudate and the putamen, known as the dorsal striatum are part of the basal ganglia and its role in language studies will be discussed soon in this section.

A large cluster for reading the L1 in bilinguals is located in the temporal lobe involving the bilateral hippocampal area (total of 1,347 voxels at mean *T* = 6.20, *p* <.001), which is habitually implicated in memory retrieval and considered "a potentially key contributor to cognitive functions that require on-line integration of multiple sources of information, such as on-line language processing" (Duff & Brown-Schmidt, 2012, p.1). Large clusters are also located in visual association areas in the occipital lobe (BA18 & 19: total of 412 voxels at mean *T* = 4.97, *p* <.001), regularly implicated in orthographic processes (Bolger et al., 2005). Participants displayed activation in the left IPS (91 voxels at *T* =5.01, *p* <.001), typically associated with visuo-spatial processing (Newman et al., 2003), possibly due to the generation of visual images of the actions depicted in the sentences. A small cluster is recruited in the right cerebellum (22 voxels at *T* = 4.79, *p* <.001). The role of the cerebellum as a coordinator of motor function is well established, but according to De Smet and colleagues (2013), a number of studies have extended the role of the cerebellum to the modulation of cognitive, linguistic and affective processing, such as "non-motor associative learning, working memory, visuo-spatial abilities, verbal fluency, syntax, reading, and writing" (p.339). Cabeza and Nyberg (2000), in their review of 275 PET and fMRI studies, found cerebellar activation to be related "to the articulatory level of speech production" (p.15) and "memory search processes" (p.21). However, the precise role of the cerebellum in reading comprehension remains to be understood. In addition, our participants recruited a small cluster important to reading in the left angular region (16 voxels at *T* = 4.66, *p* <.001). According to Shaywitz and Shaywitz (2005), this area is related to phonological (grapheme to phoneme) conversion. Stoeckel and colleagues (2009) demonstrate in their study that the angular gyrus is also implicated in semantic memory.

Reading in English contrasted to fixation elicits, in late bilinguals, more clusters in the frontal lobe: the left inferior frontal *pars triangularis* (765 voxels at *T* = 5.86, *p* <.001), involved in semantic processing, the left SMA (750 voxels at *T* = 6.78, *p* <.001) and precentral regions (total of 223 voxels at mean *T* = 5.09, *p* <.001), both involved in silent articulation. In the temporal lobe, two clusters with peaks in the left middle temporal region and one cluster in the right Heschl's gyrus (extending to the parietal lobe) encompass Brodmann areas (BAs) 21, 22 and 39. A total of 1,107 voxels (mean *T* = 6.74, *p*

$<.001$) seem to be involved in phonological processing (Bolger et al., 2005; Dehaene, 2009). A cluster in the left inferior temporal area ($T = 4.77$, $p < .001$) and two clusters in the bilateral hippocampus (larger in the RH: total of 53 voxels, mean $T = 5.13$, $p < .001$) are believed to be implicated in semantic and memory retrieval processes (Bolger et al., 2005; Duff & Brown-Schmidt, 2012). The largest area of activation is located in the occipital lobe involving BAs 17, 18 and 19 (6 clusters with a total of 3,174 voxels at mean $T = 6.40$, $p < .001$). Their peaks are at the left-lateralized posterior cingulate and parahippocampal, and at the right-lateralized lingual, calcarine and superior occipital. It is believed that these areas, because they are traditionally regarded as visual cortex and visual association areas, participate in the visual recognition of words and in orthographic processes (Bolger et al., 2005). Bilinguals reading in their L2 also recruit the left IPS (81 voxels at $T = 4.75$, $p < .001$) which is believed to be engaged in visuo-spatial processing (Newman et al., 2003) and also believed to be part of the discourse network (Mason & Just, 2006).

By adding the amount of voxels in each cluster in each language (table 4.1), we reach the number of 3,333 voxels recruited for bilinguals reading in Portuguese and 6,184 voxels for the same bilinguals reading in English. It is interesting to note that from the total numbers, reading in Portuguese recruits 2,669 voxels in the left hemisphere (LH) and 664 in the right hemisphere (RH), while English recruits 3,735 voxels in the LH and 2,449 in the RH. Our results are in consonance with Marian and colleagues' (2003), Yang and colleagues' (2011) results at the word level, and with Hasegawa and colleagues' (2002), and Buchweitz and colleagues' (2009b) results at the sentence level. Such studies have investigated different pairs of languages (Russian-English, Chinese-English, and Japanese-English) in late bilinguals and have reached the same conclusion that bilinguals rely on a more widely distributed neural system in the processing of L2 than of L1. Saur and collaborators (2009) found higher levels of activation mainly in the left IFG for processing the L2 in late (German-French and French-German) bilinguals. In the present study, higher levels of activation in the SMA for processing the L2 than the L1 were found. The literature about L1 processing seems to agree that SMA activity is associated with articulatory processes during comprehension (Gitelman et al., 2005; Jobard et al., 2011). Our results follow Buchweitz's (2006) that the SMA "is clearly associated with language processing in both the L1 and the L2; however, it was more significantly activated in the second language" (p.98).

Despite presenting a difference in number of active voxels, our findings suggest that bilinguals display a high degree of overlapping activity (Paradis, 2004; Buchweitz, 2006) when reading in their L1 and in their L2. Both languages display overlapping activity in left motor areas, left IPS and occipital visual areas. In the IFG, the L1 recruited more voxels in the *pars opercularis* (BA44) while the L2 recruited more voxels in the *pars triangularis* (BA45). Remarkably, BA 45 is positioned anteriorly in relation to BA 44 in the brain. Such a fact will add evidence for a later discussion about a more anterior representation of the L2.

At the word level, analysis of top stable voxels revealed that bilinguals reading in Portuguese recruit a set of areas predominantly left lateralized in parietal, frontal and temporal lobes. A total of 1,096 voxels are stable across presentations, 1,010 located in the LH and 86 in the RH. Inferior, middle and superior frontal regions corresponding to BAs 6, 8, 9 and 44 are recruited (total of 74 voxels in the LH and 4 in the RH), traditionally associated with semantic processes and phonological processes (Bolger et al., 2005). The largest amount of voxels (989: 933 in the LH & 56 in the RH), located in the parietal lobe, encompass BAs 7 extending to 31, 7 extending to 40, 19, and 19 extending to 39. Such areas seem to be involved in phonological and orthographic processes. Twenty-nine voxels (26 in the RH & 3 in the LH) are stable in the temporal region (BAs 37 & 39), normally implicated in semantic access and visual analysis (Dehaene, 2009; Bolger et al., 2005). It seems that the processing of the L1 engages the traditional language network.

Bilinguals reading in English present 1,381 stable voxels, predominantly left lateralized (1,296; 85 voxels in the RH). A total of 194 voxels are located in the frontal lobe encompassing left superior medial, left IFG *pars triangularis*, bilateral IFG *pars opercularis*, left middle and left SMA. As previously mentioned, these areas are associated with semantic access (BA45), phonological and syntactic processes (BA44), and articulatory procedures (BA6). A total of 1,149 stable voxels are located in the parietal lobe engaging BA7 regions (1098 in the LH; 51 in the RH), an area typically engaged in retrieving words from long-term memory and accessing the phonological store (Cabeza & Nyberg, 2000). As well, 38 voxels (29 in the RH; 9 in the LH) are recruited in the occipito-temporal region (BAs 19 & 39) which are believed to support visual analysis, thus, orthographic processes (Bolger et al., 2005; Dehaene, 2009). It seems that processing the L2 is engaging the language network as well as the anterior attention network.

It is interesting to note that English, as exhibiting a deep orthography, engages more right hemisphere activation for orthographic processes. Our findings are similar to those encountered by Chee and colleagues (1999). They investigated sentence reading in Mandarin-English early bilinguals and found activation in the same areas we did, but also in the left temporal region (BAs 21, 22 & 38). In this study such areas were not found in the stability analysis but found in the reading > fixation analysis. Chee and colleagues relate activation in BA7 to verbal working memory (WM) function as well as activation in BAs 6, 9 and 46. Bledowski and colleagues (2009) confirm such a point by explaining that WM relies on the ability to maintain stable active representations. In our study, participants had to keep phrases active in their memory for comprehension. A sentence such as '*The child broke the glass in the restaurant'* appeared one phrase at a time: *The child, broke, the glass, in the restaurant*. Therefore, participants had to keep the words, the meaning active in their memories to be able to form a complete representation of the sentence at the end of it (before fixation). As mentioned previously, SMA activation is significant since readers articulate, repeat information in their minds to assist comprehension (Buchweitz, 2006).

As regards the representation of concepts/words in the brain, lesion studies proposed that the language system is composed primarily of two domain regions: Broca's (left IFG) and Wernicke's areas (left STG). Just and colleagues (1996), the first study with fMRI about sentence processing, confirmed the view about the recruitment of classic LH areas (BAs 22, 44 & 45) and suggested the involvement of the RH homologues when sentences are structurally more complex. The present study, as many others in the literature, suggests that it is not only a small set of regions. Researchers have found widespread sets of regions involved in all aspects of language processing. To recognize words, our participant-readers recruited areas dedicated to visual, phonological, and semantic analysis irrespective of being the language the participants' L1 or the L2. It is believed that they made use of the phonological and the lexical routes, as proposed by Frost and colleagues (1987) and Dehaene (2009). The grapho-phonological route (Jobard et al., 2011) involves accessing meaning of the words via their pronunciation, it means, by linking orthographic units to their phonological equivalents. The lexico-semantic route pairs orthographic forms of words and the semantic representations they stand for. Relating these routes to Gagné and colleagues' component processes of reading, the phonological route would be related to recoding (converting letters into speech sounds) and the lexical route would be related to matching (accessing meanings directly from visual input). Brain activation of the visual cortex, temporal and frontal regions for reading sentences in both the L1 and the L2 in the present study confirm such perspective. Such result follows Dehaene (2009) when he states that both routes are automatically activated during word recognition and act in parallel to mediate semantic access. As well, our results seem to add support to the claim that the bilingual's languages are stored in memory as a shared system for representation. Differences in the processing of the two languages seem to be a reflection of processing requirements.

It became clear from the analyses at the word and sentence level that the L2 recruited more voxels in the left and right hemispheres. In the stability analysis, the number of voxels in the RH is comparable in the L1 (86 voxels) and in the L2 (85 voxels). In terms of associative and visual cortices, counts of stable voxels reveal that English exhibits more active voxels in the left associative cortex (194; 164 in Portuguese) and in the right visual cortex (4; 2.42 in Portuguese). With regard to the right associative cortex, both languages display similar number of stable voxels (108 in Portuguese; 107 in English), and concerning the left visual cortex, the L1 shows more active voxels (4.67; 3.5 in English). At the sentence level, reading in the L2 recruited a greater amount of voxels in the RH (664 for the L1; 2,449 for the L2). Such a fact may be explained by the dynamic spillover of the added computation hypothesis (Prat et al., 2007). It suggests that the additional activation for the L2 in the RH is the result of a spillover of activation; it means that the L2 comprehension exceeded the limits of LH processing and activation "spilled over" the right hemisphere homologues. Our findings indicate that L2 sentence comprehension places additional workload in the brain systems.

In order to add to the discussion, language difference results (reading in Portuguese > reading in English and reading in English > reading in Portuguese) seem to confirm what was discussed above. Reading in English recruits only 16 different voxels (p <.001) from the ones recruited by reading in Portuguese in our bilinguals. These voxels are located in the right middle occipital region, adjacent to the angular gyrus and they may be reflecting phonological and semantic processes as well as the conversion grapheme-phoneme (Shaywitz & Shaywitz, 2005; Stoeckel et al., 2009). It is interesting to note the recruitment of such an area in the right hemisphere, a fact that may be considered an effect of the spillover of activation (Prat et al., 2011). In turn, reading in Portuguese does not require the recruitment of any additional voxel (p

<.001) from the ones recruited by reading in English. From the analysis, it seems possible to conclude that the brain activation for the processing of L1 and L2 converges.

L2-L1 differences were expected to reflect the "additional cognitive processes of reading in a foreign language" (Buchweitz et al., 2009, p.141). As regards number of voxels and laterality, results from this analysis seem to hold that the L2 engages some more voxels and adjacent areas bilaterally than the L1. In addition, findings suggest, especially in figure 4.18, that the L2 displays a more anterior representation while the L1 is represented more posteriorly. Evolutionarily thinking, the frontal lobe is the most recently-evolved part of the human brain, and during brain development, maturation progresses "in a back to front direction over the primary motor cortex and eventually, at the end of adolescence, to the prefrontal cortex" (White, n.d., p.17). Thus, it is reasonable to assume that the L2 would be represented more anteriorly than the L1 in late bilinguals. At this point, this is merely an interpretation, more studies are needed to confirm or refute this viewpoint. Here it seems to fit Prat and colleagues' (2007) concept of neural adaptability: the dynamic configuration of neural networks as a function of the cognitive demands imposed by the tasks individuals perform. It is believed that as individuals learn an L2, as they develop their skills, "the brain seems to be able to fine-tune the cognitive mechanisms" (Buchweitz, 2006, p.71) required for the processing of the L2.

At the CCBI lab, my colleagues and I created the CCBI features, a set of 42 features intended to describe a semantic property as well as correspond to a known or plausible neural mechanism (Just et al., 2010). We believe that semantic properties of words are decisive for understanding the differences in the topography of brain activations (Pulvermüller, 1999). To simplify the analysis, features were grouped into nine groups and the most interesting results will be discussed. In the group *part of speech*, *verbs* and *adjectives* present remarkable activation in left parietal regions for the L2, which may be interpreted as participants' imagining the actions depicted in the sentences. In the group *perceptual characteristics*, one can find features such as *man-made, natural, inanimate, appearance, size, color, valence and intensity*. For this group, the L2 presents notable activation in bilateral frontal and left fusiform areas, which are interpretable as visual features relying more on physical properties (color, size, appearance) and as man-made objects and inanimate entities relying more on their functional properties

(Barsalou, 2008; Anderson, 2010). The group *domain of human activity* counts with features such as *health, eating/drinking, communication, conflict, sports, technical, finance, humanities, law, political/governmental event or entity* and *knowledge*. The L2 presents more active voxels in the right frontal and left fusiform, while the L1 presents more voxels in the left frontal and left parietal. LH frontal activation is related to the *eating* factor from Just and colleagues (2010). The fourth group, *animate beings*, includes features such as *person, animal* and *human group* and recruits the fusiform area only for the L2 because of their physical properties (Barsalou, 2008). The group *time/space* puts together the following features: *setting, unenclosed, location saliency, shelter, change of location, event* and *time of event*. The L2 recruits bilateral fusiform and frontal regions for this group, what is in line with the shelter factor proposed by Just et al. (2010). *Physical action or state* groups *physical action, change of physical state* and *impact* features and generates in this study bilateral fusiform and occipital activation for the L2. The groups *mental action or state* (*mental act, perceptual event, emotion,* & *transfer of possession*) and *social action or state* (*social interaction* & *social support*) present a similar pattern of activation: the L2 recruiting bilateral frontal and visual-related areas. The last group *abstraction* presents more bilateral fusiform and subcortical activation. As it could be noticed, voxels in visual areas respond to any feature in the L2. The L1, interestingly, presents predominantly left parietal activation for most of the features, except for *social action or state* that displays more activation in the bilateral frontal cortex. In the groups *perceptual characteristics, domain of human activity* and *mental action or state*, the L1 present, besides the left parietal activation, bilateral frontal activity. Overall, the number of stable voxels is left lateralized for Portuguese and bilateral for English. One may conclude that in proficient bilinguals, semantic processes overlap and the majority of the differences may be attributed to orthographic differences between the languages.

In short, the answer to our research question *Are both languages (Portuguese and English) represented and processed in the same areas of the brain? If so, to what extent?* is in accordance with the hypothesis posed in the Method chapter. Analyses conducted at the word and sentence levels suggest that the bilingual brain makes use of overlapping areas for processing the L1 and the L2, as reported by studies at the word level (Illes et al., 1999; Crinion et al., 2006; Isel et al., 2010; Buchweitz et al., 2012; Correia et al., 2014) and at the sentence level (Chee et al., 1999; Yokoyama et al., 2006). Despite the high degree of overlap, bilinguals rely on a more widely distributed set of areas when processing the L2 and these additional areas are typically located in the right hemisphere, in accordance with studies at the word level (Marian et al., 2003; Yang et al., 2011; Jamal et al., 2012; Hernandez et al., 2015) and at the sentence level (Hasegawa et al., 2002; Wartenburger et al., 2003; Buchweitz, 2006; Buchweitz et al., 2009b). These additional areas are believed to reflect increased cognitive effort/demands for processing the later learned language (Perani, 2005). As expected, more visual areas were recruited for the processing of English than for the processing of Portuguese (Buchweitz et al., 2006, 2012). As regards the representation of concepts, the present study adds support to the claim that conceptual knowledge is organized in a widely distributed complex network in the bilingual brain (Marian et al., 2003; Buchweitz & Prat, 2013; Sousa & Gabriel, 2015), and we believe that the differences between the L1 and the L2 are due to processing requirements.

5.2 RQ2: THE REPRESENTATION AND PROCESSING OF L1 IN THE BILINGUAL AND THE MONOLINGUAL BRAIN

As aforementioned, a great number of studies in the bilingual literature have compared the brain activity yielded by the processing of the first versus the second language within the same individuals. Despite this focus, research has not concentrated on the direct study of language processing in the brains of bilinguals compared to the brains of monolinguals. After detailed search, I could find only three studies (Kovelman et al., 2008; Parker Jones et al., 2012; Palomar-García et al., 2015) that directly compared brain activation of a group of bilinguals to the brain activation of a group of monolinguals reading in their L1. Kovelman and colleagues' (2008) and Palomar-García and colleagues' (2015) studies were conducted with early bilinguals, while Parker Jones and collaborators' study recruited a sample of mixed bilinguals (three groups of varied AoA: from 1 to 15 years old). The 2008 study investigated English monolinguals and Spanish-English bilinguals; the 2011 study examined English monolinguals and bilinguals with heterogeneous L1s and English as the L2; and the 2015 study investigated Spanish monolinguals and Spanish-Catalan bilinguals. Considering these pieces of information, to this researcher's knowledge, the present study is the first to compare Portuguese monolinguals and Portuguese-English late bilinguals. In this section, I discuss the monolingual results reached by sentence- and word-level analyses:

reading > fixation, stability analysis and the differences between monolinguals and bilinguals processing the L1.

At the sentence level, monolinguals reading in Portuguese (contrasted to fixation) recruited a set of occipital, frontal, subcortical and cerebellar areas. The largest cluster is located in the right lingual (58 voxels at $T = 5.68$, $p < .001$) and in the left calcarine with peaks in the superior occipital and in the right lingual (34 voxels at $T = 5.17$, $p < .001$). Such areas are normally implicated in the identification and recognition of words (Mechelli et al., 2000; Abutalebi et al., 2001). Three clusters in the left frontal lobe: superior frontal (BA4, 27 voxels at $T = 5.95$), cingulate (BA24, 19 voxels at $T = 5.69$), and middle frontal (BA6, 35 voxels at $T = 5.19$) are traditionally involved in phonological processing and WM functions (Bolger et al., 2005; Bledowski et al., 2009). A cluster in the left thalamus extending to the posterior caudate is recruited (45 voxels at $T = 5.28$). According to Crinion and colleagues (2006), the thalamus and the caudate play "a critical role in controlling and selecting automatic motor sequences such as those necessary for articulation" (p.1540). Bialystok and colleagues (2009) explain that basal ganglia structures, including the caudate, are engaged in language selection, switching processes, language planning and lexical selection. Some studies have suggested that the left caudate plays a role in lexical-semantic control in both monolingual and multilingual subjects (Crinion et al., 2006). However, the role of such subcortical structures in monolingual reading comprehension is not well documented. Reading Portuguese also engages the left cerebellum (17 voxels at $T = 5.43$) in monolinguals. As discussed in the first section of this chapter, the precise role of the cerebellum in reading comprehension remains to be understood (De Smet et al., 2013).

At the word level, monolingual reading in Portuguese exhibits a large cluster of stable voxels in the left precuneus (431 voxels). Interestingly, such cluster is located at the same coordinates as the cluster (907 voxels) recruited by bilinguals reading in their L1. Such an observation seems to add evidence to the inference drawn previously that bilinguals recruit more widely distributed brain areas when reading in their L1. As already discussed in the previous section, the precuneus has been associated with visual-spatial imagery, episodic memory recollection and perspective taking (Cavanna & Trimble, 2006). Its stable activation may be reflecting the three processes, since our participants were reading sentences silently and were instructed to generate vivid mental representations of the meaning of each sentence.

Contrasting monolingual reading in Portuguese > bilingual reading in Portuguese at the sentence level did not elicit any active clusters, as in Kovelman and colleagues' study (2008). On the other hand, by comparing the condition bilingual reading in Portuguese minus the condition monolingual reading in Portuguese, it is possible to find four active clusters. The largest cluster peaks at the right putamen (48 voxels at $T = 4.83$, $p < .001$), a region already discussed in the previous section, that needs further investigation to unveil its role in reading comprehension. Forty-five voxels are recruited by bilinguals in the left middle temporal area (BA22, $T = 4.82$) typically engaged in semantic access and phonological processing (Dehaene, 2009). The third cluster is located in the left inferior parietal region (23 voxels at $T = 4.01$). Such an area is typically associated with phonological processing and short-term retention of linguistic information in studies of syntactic complexity (Keller et al., 2001) and tongue-twister effects (Keller et al., 2003) in monolingual sentence comprehension; with the mapping between orthographic, phonological and semantic systems in monolingual language processing (Hernandez et al., 2015), as well as with the maintenance of representations and WM functions (Bialystok et al., 2009). The last cluster, the right precentral (10 voxels at $T = 3.94$) is believed to be involved in silent articulation. Parker Jones and colleagues (2012) also reported precentral activation, but in the LH, for bilinguals compared to monolinguals reading in their L1 (English). Our results suggest that bilinguals may be engaging more cortical areas for phonological and semantic processing (Bolger et al., 2005) of the L1. As well, results seem to indicate that bilinguals engage the phonological network more than monolinguals reading the L1. Such a result may suggest that being a bilingual changes the way individuals process their L1 (Bialystok et al., 2009).

Monolinguals and bilinguals reading in Portuguese also recruit overlapping areas. From figure 4.11, it is possible to observe (at $T = 3.55$, $p < .001$) that clusters emerge in left-lateralized posterior frontal and middle temporal areas, small clusters in left parietal regions, and a few clusters in right-lateralized areas, with emphasis to a cluster in the right occipital, bigger than the left occipital cluster that, in turn, is closer to the cerebellum. Kovelman and colleagues (2008) also found overlap in the brain areas recruited by monolinguals and bilinguals reading sentences in their L1 and judging the plausibility of them. As well, Parker Jones and collaborators (2012) observed a degree of overlap in the cortical regions engaged by monolinguals and bilinguals naming pictures, reading words silently and performing lexical decision tasks.

The three studies reviewed and the present study encountered differences in the bilingual minus monolingual condition. In Kovelman and colleagues (2008), bilinguals had increased activation in the left inferior frontal cortex (within BAs 44 & 45 at $T = 4.35$, $p <.001$). Parker Jones et al. (2012) observed more activation in six left-lateralized regions: planum temporale, precentral, superior temporal, *pars opercularis*, *pars triangularis* and insula (at mean Z[42] $= 5.16$, $p <.05$). Palomar-García and colleagues (2015) reported (at mean $Z = 3.15$, $p <.05$) more activation in the left precuneus and right superior temporal areas for the picture-naming task; and increased activation in the right posterior superior temporal gyrus for the passive listening of words. At a less strict threshold ($T = 1.72$, $p <.05$), our results also reveal a large cluster of voxels in the left *pars triangularis* (1156 voxels at $T = 3.24$), left precentral (14 voxels at $T = 2.06$), right superior temporal areas (522 voxels at mean $T = 2.71$) and left precuneus (177 voxels at mean $T = 2.05$). Despite methodological differences, monolinguals and bilinguals seem to recruit similar brain areas to process language. Nevertheless, bilinguals seem to display more activation in such areas and seem to even recruit other areas to process their L1.

Bialystok and colleagues (2009) reveal that adult bilinguals normally take longer to retrieve words than monolinguals do, and generate fewer responses when asked to list words by a specific initial letter. Bilinguals exhibit more processes related to the executive control of language mainly because they have to deal with candidates from both L1 and L2 simultaneously activated (Schwartz & Kroll, 2006). Monolinguals do not have to deal with such a competition in their brains. Parker Jones and colleagues (2012) elucidate that bilinguals, by knowing the words for a concept in two languages, ought to selectively activate the target language trying to minimize competition for word selection from translation equivalents in the nontarget language. As well, monolinguals use the same language on a daily basis while bilinguals use two languages, the reason why the words in each of the bilingual's languages are less used than the same words in the unique language a monolingual speaks.

Briefly, the answer to our second research question *Are the same areas recruited for processing sentences in Portuguese for monolinguals*

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[42]Parker Jones and colleagues (2012) and Palomar-García and colleagues (2015) report Z values because their sample sizes are above than 30. T values are normally reported in studies that have less than 30 participants (<http://www.statisticshowto.com/when-to-use-a-t-score-vs-z-score/>).

and bilinguals? If so, to what extent? is also partly consistent with our hypothesis. Our findings seem to converge with the findings from bilinguals reading in the L2, that the L2 engages more voxels and adjacent cortical areas bilaterally than the L1. Analysis conducted at the word and sentence levels of monolinguals and bilinguals reading in their L1 revealed that bilinguals engage a more complex network of areas even to process their L1 (Kovelman et al., 2008; Parker Jones et al., 2012). We may conclude that “the advantage of being bilingual comes at the expense of increased demands on word-retrieval and articulation” (Parker Jones et al., 2012, p.901), even in a task involving reading comprehension of simple sentences. We expected to find increased activation in the right superior temporal gyrus for bilinguals reading in their L1 (as Palomar-García et al. (2015) found), but we did not find it. We found increased activation in right-lateralized regions, as predicted, the right putamen and the right precentral, and in left-lateralized regions as the middle temporal area and the inferior parietal region, showing that bilinguals recruit additional bilateral areas. According to Bialystok and colleagues (2009), language processing should be understood as recruiting processes from the general cognitive system. In the light of such an observation, we may perceive the additional recruitment of areas by bilinguals reading in their L1 as attentional management processes. In Bialystok’s words (2011), “the executive control circuits needed to manage attention to the two languages became integrated with the linguistic circuits used for language processing, creating a more diffuse, more bilateral, and more efficient network that supports high levels of performance” (p.236).

5.3 RQ3: SEMANTIC NEURAL REPRESENTATION IDENTIFICATION

The answer for the third research question used the method developed at Carnegie Mellon University to decode mental states from fMRI (Mitchell et al., 2003, 2004, 2008a; Shinkareva et al., 2008; 2011; 2012; Just et al., 2010). It is based on multi-voxel pattern analysis and machine learning procedures to automatically identify the cognitive state of an individual based on the neural response to a task. The present study follows the neurosemantic theory proposed by Just and colleagues (2010). In that occasion, the researchers worked with concrete nouns and identified semantic factors related to those nouns. Here, we sought to identify the thought, generated by concepts in the context of sentences, based on the underlying brain activation patterns. In addition, we investigated the extent to which there is commonality in the neural representation of concepts across people and across languages as well as the ability to predict the activation pattern for a concept not seen previously based on the model of the content of the representation.

As the method is a recent innovation, there are, to our knowledge, only three studies which have examined the possibility of using brain activation patterns to identify the semantic representations in two languages. The first, Buchweitz and colleagues (2012), investigated concrete nouns of two categories (tools & dwellings) presented visually to 11 Portuguese-English late bilinguals. The second, Correia and colleagues (2014), explored concrete nouns of two categories (animals & objects) presented auditorily to 10 Dutch-English bilinguals. The third, Zinszer and colleagues (2015), examined seven monosyllabic words of different categories presented visually to 11 native speakers of English and 11 native speakers of Chinese. As regards the tasks, participants were asked to think actively about the properties of the words in the first study; to actively listen to the words and press a button whenever they hear an object in the second study; and to perform a semantic relatedness task in the third study. Innovations in the present study are two-fold: it is the first to investigate sentences presented visually and the first to recruit bilinguals and monolinguals for the same study. Twelve Portuguese-English late bilinguals and nine Portuguese monolinguals thought of simple sentences while they were fMRI scanned. They were asked to think actively about the meaning of the sentences, creating a vivid mental representation.

We employed different classifiers and reached the conclusion that sentence reconstruction with semantic features (CCBI features) and case roles based on the neurosemantic locations derived from three independent English monolingual speakers (Wang et al., 2016). The success of applying them to predict sentences in Portuguese native speakers (bilinguals and monolinguals) might indicate that these locations constitute a language-independent concept network. We conducted within-language (training in Portuguese and testing in Portuguese; training in English and testing in English) and cross-language (training in Portuguese and testing in English; training in English and testing in Portuguese) classification.

For bilingual within-Portuguese classification of sentences (within participants), the mean rank accuracy in this study was 63.4% (*SD* = .07), the same rank accuracy (.63; *SD* = .06) reported by Buchweitz and colleagues (2012). For monolingual within-Portuguese, the mean rank accuracy was 66.4% (*SD* = .09). The highest classification rank accuracies were: 80.8% for bilingual within-Portuguese and 75.8% for monolingual within-Portuguese classification. Within-English classification, in turn, yielded a mean accuracy of 66.8% (*SD* = .07). In Buchweitz et al.'s study, the mean rank accuracy was .60 (*SD* = .08). The highest classification rank accuracy was 79.5% for within-English. In Buchweitz et al.'s study, the highest accuracies were .72 for within-Portuguese and .71 for within-English. It is relevant to highlight that in the two studies different procedures were used especially because one dealt with single words whereas the other dealt with sentences. Buchweitz et al. used GNB classification that in our study yielded lower rank accuracies (within-Portuguese: mean 59.2%, best 67%; within-English: mean 60.9%, best 71.9%). In both studies, within-language classification confirmed the ability to identify thoughts associated with concrete nouns and sentences in the participants' L1 and L2.

In the reviewed studies, none of them reported between-participants sentence prediction. We conducted between-participants classification only for Portuguese (in monolinguals and bilinguals) to investigate sentence prediction in Portuguese using the cubes derived from independent English data. For such an analysis, we selected 15 participants with the best rank accuracies. The mean accuracy for the group was 63.6% (*SD* = .04) and only one test participant accuracy could not reach significance (rank accuracy $\geq$ 56%, $p < .05$). In addition, we selected the best five ranked sentences from the generative model in a set of perfectly predicted sentences (rank accuracy = 100%) to investigate the extent to which the model made the predictions systematically on the gist of each sentence. The result revealed that the prediction algorithm not only 'guessed' the target sentence correctly by putting it at the top, but also ranked the following sentences systematically based on shared semantic features. Such a feat could be accomplished because our generative model is based on human-interpretable semantic features. Interestingly, by adding the neurosemantic cuboids derived from independent data collected with three English monolingual readers, the model seems to be able to predict sentences in monolingual and bilingual Portuguese speakers. Therefore, this result indicates that the locations may constitute a language-independent concept network. Building up on Just and colleagues' study (2010) that identified four factors (shelter, manipulation, eating & word length), the present study contributes to the area by revealing six semantic factors (social interaction, well-being, action, shelter, eating, and natural perception) that might be encoded in common neural areas across languages.

Additionally, the three recent studies reviewed (Buchweitz et al., 2012; Correia et al., 2014; Zinszer et al., 2015) have shown that mental representations of words (concrete nouns) are decodable across languages, since there are commonalities in the representations of concepts. Zinszer and colleagues were able to decode words with 100% of accuracy in independent groups of English and Chinese speakers. They conclude that their study " illustrates the possibility of achieving neurally informed translation in the future based on the relative similarity of native speakers' neural responses to words in each language" (2015, p.5). From a methodological point of view, the reader of their article does not encounter in the text any information regarding the participants' knowledge of the other language (English for Chinese natives; and Chinese for English natives). Assuming that the data was collected in Dartmouth College in the USA, the reader may ponder whether these participants, since they are living in the USA, are truly monolinguals (who cannot communicate in another language besides their L1). Correia and colleagues (2014) found evidence, in bilingual listeners, that "semantic-conceptual knowledge is organized in language-independent form in focal regions of the cortex" (p.336). Their cross-language analysis relied on the semantic properties of the nouns. Buchweitz and colleagues (2012) demonstrate that semantic processing is organized over a common network of areas in the brain, allowing the reliable decoding of nouns across languages.

Our results reveal that for the classification of brain activation from English to Portuguese (E to P) the mean rank accuracy of sentences in our 12 bilinguals was 66.5% (*SD* = .06) and in our 8 best bilinguals was 68.9% (*SD* = .06). Our best participant had an accuracy of 79.2%. Comparing to Buchweitz and colleagues' study with words, their mean rank accuracy was 68% (*SD* = .11) and the best accuracy was 82%. We also trained our model to identify brain activation in the other direction, Portuguese to English (P to E). The mean rank accuracy for our 12 bilinguals was 64.7% (*SD* = .06); for our 8 best bilinguals, 67.6% (*SD* = .05). Our best participant had an accuracy of 74.4%. Buchweitz et al. had a mean rank accuracy of 72% (*SD* = .08) and their best rank accuracy was 89%. Comparing the directions, Buchweitz and colleagues had better rank accuracies training the data in the participants' L1 and testing in their L2. We observed an opposite trend; we had slightly better rank accuracies training the data in the participants' L2 and testing in their L1. Such small difference in direction in our data might be due to the higher level of activation as well as to the more distinct patterns of activation displayed by our participants in the L2 than in the L1. We reasoned that Buchweitz and colleagues might have displayed better rank accuracies for the L1 to the L2 as a result of the higher number of stable voxels in Portuguese (103.4) than in English (95.3). The authors claim that "the more proficient the bilingual, the better the prediction of L1 brain activation using L2 brain activation" (Buchweitz et al., 2012, p.287). They assessed proficiency by means of self-ratings in a language background questionnaire whereas the present study applied a similar questionnaire as well as an adapted version of the reading section of a standardized proficiency test. Nevertheless, more research will possibly help clarify why one direction of prediction displays better rank accuracies in detriment of the other.

In short, the answer to our third research question *Is it possible to identify the semantic neural representation of sentences in one language based on the brain activation for the same sentences in another language in late bilinguals? How? With what accuracy?* is in line with our hypothesis. Our findings suggest, as predicted, that the commonalities in the representations of words and sentences across languages are sufficient to allow the successful decoding of words and sentences across languages. In light of earlier studies that revealed similarities in neural representations across different stimulus types (drawings, word format) (Mitchell et al., 2008a; Shinkareva et al., 2008, 2011, 2012; Just et al., 2010; Buchweitz et al., 2012; Correia et al., 2014; Zinszer et al., 2015), the present study contributes to the area by suggesting that the universality in the representation of meaning goes beyond the level of specific languages or stimulus types. Remarkably, the model generated reasonable accurate predictions of the neural representation of sentences based on simple addition of words (a set of 96 words in the context of sentences). Such results might pave the way for cross-language and cross-modality decoding of complex conceptual constructs in addition to advance the theories of bilingualism and of the 'language of thought' (Marcus, Marblestone & Dean, 2014).

5.4 RQ4: INDIVIDUAL DIFFERENCES IN L2 PROFICIENCY AND WMC

A number of studies in the monolingual and bilingual reading comprehension literature have examined effects of individual differences in working memory capacity and proficiency level. Most of the bilingual studies reviewed in the present work controlled for proficiency by applying subjective and/or objective measures of proficiency (Buchweitz, 2006; Jamal et al., 2012; Hernandez et al., 2015; among others). Behavioral studies relating WMC and L1 and L2 performance are numerous (see Bailer, 2011). Neuroimaging studies (Prat et al., 2007; Buchweitz et al., 2009; Prat & Just, 2011) have revealed that high capacity readers display three key properties: "(1) greater efficiency (accomplishing the same task with less activation); (2) greater adaptability (more modulation of activation as a function of variation in the task demand); and (3) higher inter-center synchronization (higher functionally coordination)" (Mason & Just, 2013, p.154). In the following, we discuss the results of the analysis of bilingual reading and level of proficiency and the analysis of WMC effects in bilingual and monolingual reading.

In the literature, few studies compare the effects of the degrees of proficiency in reading comprehension processes in the brain. Meschyan and Hernandez (2006), in their study with Spanish-English bilinguals, found that the less-practiced language (in their case, the L1) requires greater articulatory motor effort. Wartenburger and colleagues (2003) investigated two groups of fluent Italian-German bilinguals: one who learned the L2 at an early age and another who learned the L2 at a later age. They concluded that proficiency level plays a role in semantic processing while AoA, in grammatical processing. Nevertheless, to the knowledge of this researcher, no studies have published results as regards the comparison, within a low variability sample, between the areas activated by bilinguals with a lower level of proficiency and bilinguals with a higher level of proficiency.

In the present study, bilinguals showed a good level of proficiency in the L2 (mean = 8.53; *SD* = 1.16; range 6.7-10). L1 proficiency was not assessed objectively, but this researcher assumed that all of them were proficient in Portuguese since, in the language background questionnaire, they reported using Portuguese for some time on a daily basis and they were able to communicate fluently with the researcher. Findings show that higher L2 proficiency is associated with left superior temporal activation (27 voxels at $T = 7.49$, $p < .001$). Abutalebi and colleagues (2001) revealed that early bilinguals display activation along a left-sided network of classical language areas: superior and middle temporal gyri, the angular gyrus, "the temporal pole, a structure which seems specifically engaged by sentence and discourse level processing" (p.187), and the inferior and middle frontal areas involved in lexical monitoring. In the case of late bilinguals, they argue that the degree of proficiency shapes the cortical organization of languages, with high proficiency in the L2 showing greater overlap with the L1 cortical areas. Comparing the activation exhibited by our late bilinguals with higher degrees of L2 proficiency, the left superior temporal (BA38) traditionally associated with the temporal pole emerges as the only site modulated by proficiency. According to Jung-Beeman (2005), this area is part of the semantic integration network that "supports message-level interpretation by computing the degree of semantic overlap among multiple semantic fields" (p.515). Such network that "detects, elaborates and refines higher order semantic relations" (p.515) involves the bilateral anterior superior temporal gyrus and superior temporal sulcus extending into middle temporal gyrus and temporal pole. Thus, it seems that higher proficient bilinguals are employing the *usual* route for comprehension. According to Ferstl (2007), "the anterior temporal lobes were activated in studies both on the text and the sentence level when the integration of incoming words into a semantically based representation was needed" (p.85). As well, Perani and colleagues (1998) found significantly greater activation in the temporal poles for highly proficient bilinguals than lower proficient bilinguals. Therefore, we suggest that higher proficiency elicits greater activation in an area normally implicated in semantic integration.

In turn, three clusters are recruited when bilinguals display lower proficiency: the right middle frontal area (25 voxels at $T = 5.61$, $p < .001$), the right caudate (20 voxels at $T = 5.18$) and the left cerebellar area (15 voxels at $T = 5.40$). The coordinates of the middle frontal cluster are associated with the BA10, prefrontal cortex, a brain region typically implicated in executive control. In Wartenburger et al.'s study (2003), low proficient bilinguals, compared to fluent bilinguals, showed increased activation in Broca's area and the right middle frontal gyrus. Our finding about the recruitment of the right middle frontal area seems to corroborate such finding. The caudate, as already discussed in this chapter, is associated with bilingual language switching, planning and lexical selection (Bialystok et al., 2009). Buchweitz and Prat (2013) explain that "the basal ganglia, which are more dopamine rich and more plastic than the cortex, seem to initiate the mappings of stimulus-response pairings, whereas the prefrontal cortex may eventually store the abstracted representations of such mappings" (p.438). Prat (2011) elucidates that the prefrontal and the striatum are frequently activated in WM studies and are recurrent "when language comprehension processes involve a large amount of cognitive control" (p.645). As regards the cerebellar involvement, De Smet and colleagues (2013) report that in some studies patients with lesions display reduced verbal fluency, while laterality studies with non-impaired subjects describe cerebellum participation in language processing as “contralateral to the activation of the cerebral cortex, even under conditions of different language dominance” (p.335). As mentioned previously in this discussion, the cerebellum has been implicated also in phonemic and semantic fluency tasks.

Briefly, it seems that our lower proficient bilinguals had to recruit the three clusters to be able to accomplish the task of understanding the sentences. Although the sentences were simple and short, it is speculated that less proficient bilinguals recruit these areas when they have to be strategic to perform the same processes higher proficient bilinguals execute naturally. Perani and colleagues (1998) argue that in low proficient bilinguals “multiple and variable brain regions are recruited to handle as far as possible the dimensions of L2 which are different from L1” (p.1849). The present study adds support to the understanding that “the connections between words in L2 and the semantic representations of the first language (L1) strengthen as proficiency in L2 increases” (Buchweitz et al., 2012, p.282). In addition, I would complement the citation by including the L2 processing at the sentence level.

As regards working memory capacity, our study applied the RST in English (Daneman & Carpenter, 1980) and its adapted version in Portuguese (Tomitch, 2003; Bailer, 2011) whose scores display a strong correlation in our sample (r = .879; p <.00). Bilinguals had a mean WMC span of 3.08 (*SD* = 0.92; *range* = 2-5.5) in Portuguese and a mean WMC span of 3.25 (*SD* = 1.03; *range* = 2-5.5) in English. The difference in scores is not statistically significant, but it is interesting to note that the L2 presents the highest mean. Taking into consideration the context in which the participants live, it seems reasonable. They were immersed in the American culture. At the time of data collection, they were working, studying, interacting to the majority of people in English. The L1 was used only to communicate with family and friends in Brazil, Brazilians in Pittsburgh, or to read the Brazilian news online. Such comparable scores seem to confirm our participants’ proficiency in the L2.

Our results show that higher WMC in bilinguals is associated with a small cluster of 5 voxels in the left superior orbitofrontal cortex (T = 3.88, p <.005), part of the PFC, traditionally implicated with WM functions. According to Frey and Petrides (2000), the “orbitofrontal region (area 11), which is primarily linked with the anterior medial temporal limbic region and lateral prefrontal cortical areas, is involved in the process of encoding of new information” (p.8723). On the other hand, lower WMC is associated with increased activation in the left-lateralized SMA (54 voxels at $T = 4.27$, $p < .005$), IFG *pars orbitalis* (19 voxels at $T = 4.05$), precuneus (5 voxels at $T = 3.68$), thalamus (14 voxels at $T = 4.33$), culmen (11 voxels at $T = 4.22$) and in the right-lateralized lingual area (61 voxels at mean $T = 3.95$). Findings seem to converge with Jobard and colleagues' (2011) results with monolinguals that "low span readers activate more regions involved in visual, phonological and semantic processing" (p.124). They found greater activation in the VWFA, left precentral, temporal sulcus, planum temporale, middle temporal and the orbitalis part of the IFG. Although not completely overlapping, our results seem to suggest that lower WMC readers may be relying on a less proficient access to written words by using phonological regions that are not engaged in higher WMC readers. As well, our participants are resorting to RH areas (dynamic spillover of activation, Prat et al, 2007). In Jobard and colleagues' words, "this pattern of results is in agreement with the hypothesis that lower performing readers have less exhaustive orthographic-to-meaning mappings, and therefore need to phonologically reconstruct the words" (p.126). As Prat and colleagues (2007), our higher WMC readers did not rely as heavily on strategic networks and occipital areas as lower WMC did.

Buchweitz and colleagues (2009a), in their study of bilingual reading and listening comprehension, found that higher and lower capacity readers "may have resorted to different strategies while reading sentences in RSVP format" (p.121). Higher capacity readers activated brain areas engaged in phonological rehearsal of information (left angular, precentral and postcentral gyri as well as right IFG), while lower capacity readers recruited significantly more voxels in the RH and in the left middle frontal gyrus, an area typically associated with executive control. Our study employed a method of presentation called moving window paradigm where one phrase appears at a time, whereas in the RSVP format, one word appears at a time. Our results are similar in the sense that lower spans recruit more RH areas, in our case, areas associated with word recognition, and divergent, in the sense that phonological rehearsal of information was employed by lower spans while our higher spans only recruited the orbitofrontal PFC.

In monolinguals, higher WMC engaged a unique cluster in the right supramarginal region (BA40, 48 voxels at $T = 5.38$, $p < .001$), which is normally implicated in phonological processing (Stoeckel et al., 2009). Such a result seems to suggest that activation for phonological processing is *spilling over* the right hemisphere in monolinguals. Conversely, lower WMC readers recruited three clusters in the temporal lobe with centroids peaking in the left superior temporal region (BA22, 43 voxels at $T = 9.90$, $p < .001$), left middle temporal area (BA21, 20 voxels at $T = 6.90$, $p < .001$) and the right parahippocampal region (BA35, 27 voxels at $T = 7.16$, $p < .001$). These areas are traditionally implicated in phonological and semantic processing (Price, 2010; Jobard et al., 2011). Our results with monolinguals are in consonance with Buchweitz and colleagues' findings (2009) that higher capacity readers activated an area of the brain associated with phonological rehearsal of information, possibly reflecting the readers' adaptation to the reading paradigm (moving window format).

As expected, lower span monolinguals and bilinguals recruited more areas of the brain than higher span monolinguals and bilinguals, possibly reflecting that higher spans exhibit greater efficient processes than lower spans (Prat, Mason & Just, 2011). Our monolingual and bilingual results seem to agree with previous studies in the area (Jobard et al., 2011; Buchweitz et al., 2009). Bialystok and collaborators (2009) postulate that the "bilingual advantage should be found in working memory" (p.104) that reflects a series of related functions concerned with holding and manipulating information that is in the focus of attention. As bilinguals need to constantly manage two active language systems and to manipulate attention to one or the other, or sometimes both, during language use, they are believed to have enhanced executive control on a variety of tasks (Grosjean, 2012). Therefore, our higher spans bilinguals exhibit greater efficiency (Prat et al., 2011) in performance than our higher spans monolinguals. In case of our lower spans, monolinguals recruit more temporal areas associated with semantic and phonological processing while bilinguals recruit a set of areas including occipital regions. Such a finding might reflect the fact that English has a deep orthography and Portuguese, a shallow one.

To sum up, the answer to our fourth research question *Do individual differences, namely proficiency in the second language and working memory capacity, modulate brain activation in bilinguals? Does working memory capacity modulate brain activation in monolinguals?* is consistent with our hypothesis. Our findings reveal that higher proficient bilinguals engaged the *usual* route for comprehension (increased activation in the left superior temporal region) while lower proficient participants had to resort to more right-lateralized language areas (Wartenburger et al., 2003; Prat et al., 2011). WMC findings suggest that lower working memory capacity monolingual and bilingual readers, besides employing right-lateralized areas, may be relying on less proficient processes to decode written input than higher WMC readers may. Lower capacity readers resorted to semantic and phonological processing areas that higher capacity readers did not. In turn, higher working memory capacity readers displayed more efficient processes than lower working memory capacity readers did. Higher span bilinguals recruited a left-lateralized frontal region associated with the encoding of new information while higher span monolinguals recruited a right-lateralized parietal region traditionally implicated in phonological processing. Indeed, the field needs more comparative studies that investigate the effects of WMC on brain activation of monolinguals and bilinguals to refine the assumption.

5.5 RQ5: WORD LENGTH AND LEXICAL FREQUENCY EFFECTS

Word length and frequency effects have been investigated in a variety of studies. Mechelli and colleagues (2000), in a PET study, studied word length and visual contrast, two variables that modulate activation in the visual cortex during reading. Just and colleagues (2010) included, as one of the semantic factors of their fMRI study, word length as reflecting "the low-level visual representation of the printed word" (p.8). Ellis (2002) conducted a review of behavioral studies to show "how frequency underpins regularity effects in the acquisition of orthographic, phonological and morphological form and that learning accords to the power law of practice" (p.144). In reading, there are frequency effects in visual word identification and of spelling-to-sound correspondences. Dehaene (2009) and Jobard and colleagues (2011) agree that more frequent words benefit from a direct link between orthographic representations and meanings, while low frequent words are more prone to the grapho-phonological route.

In bilinguals, our results show that longer words in English engage a large cluster in the left fusiform (BA37: 123 voxels at $T = 5.32$, $p < .05$) and smaller clusters in the left superior temporal area (BA42: 22 voxels at $T = 3.36$), left SMA (BA6: 15 voxels at $T = 3.30$) and right inferior occipital (BA19: 28 voxels at $T = 3.37$). Just and colleagues (2010) found word length effects in the bilateral occipital pole, lingual and fusiform gyri. Wehbe and collaborators (2014) also found effects in the occipital lobe. In addition to those areas, Mechelli and colleagues (2000) observed effects in left motor areas. In conjunction, these areas reflect visual analysis and subarticulation processes. Our results add the recruitment of the right occipital area, probably a result of the dynamic spillover of activation (Prat et al., 2011), and the left superior temporal area typically implicated in phonological processing.

Longer words in Portuguese when read by bilinguals elicit activation in the left dorsolateral PFC (BA46: 31 voxels at $T = 4.33$, $p < .05$), right fusiform (BA37: 28 voxels at $T = 4.27$), left supramarginal (BA40: 22 voxels at $T = 4.07$), right postcentral (BA3: 17 voxels at $T = 3.57$), and left inferior parietal IPS (BA7: 17 voxels at $T = 3.57$). The DPFC activation may reflect WM processes of maintaining words for subsequent processing, while the postcentral activation may reflect phonological rehearsal of linguistic information (Buchweitz et al., 2009). The IPS probably reflects visuo-spatial processing (Newman et al., 2003) and discourse processing (Mason & Just, 2006). The supramarginal gyrus, as explained by Stoeckel and colleagues (2009), is connected to auditory association regions and to a region in the IFG, both of which are implicated in phonological processing. Price (1998) considers the supramarginal the site for orthography to phonology translation. In addition, the right fusiform activation is well known as being responsible for visual word recognition.

As regards word length effects in Portuguese monolinguals, longer word reading involves a small cluster in the right superior temporal area (BA22: 15 voxels at $T = 3.18$, $p < .5$). Such area is traditionally associated with phonological processing (Dehaene, 2009; Bolger et al., 2005). The fact that longer words require the recruitment of this area in the RH seems to be an effect of spillover of activation (Prat et al., 2011). On the other hand, shorter words engage eight clusters in all lobes. In the frontal lobe, activation is observed in the right medial superior frontal (BA8: 17 voxels at $T = 4.58$, $p < .05$), left IFG *opercularis* (BA44: 23 voxels at $T = 4.07$) and the left SMA (BA6: 26 voxels at $T = 3.61$). In the temporal lobe, two clusters in the left superior temporal region are recruited, one located at BA22 (18 voxels at $T = 6.93$), and another at BA40 (29 voxels at $T = 4.43$), close to the supramarginal area. A cluster in the left insula (30 voxels at $T = 4.93$) as well as a cluster in the left middle occipital region (BA19: 17 voxels at $T = 3.38$) and a cluster in the left superior parietal (BA7: 18 voxels at $T = 3.13$). It is the first time we come across insular activation in this study. According to Zaccarella & Friederici (2015), the region has been associated with a wide range of autonomous and cognitive functions because of its highly interconnected nature. Price (2010) reported insular activation for articulatory planning processes. Active clusters seem to be reflecting phonological and orthographical processes.

As regards lexical frequency effects, bilinguals seem to recruit more right- than left-lateralized regions for processing the L2 more frequent words (such as *go*, *find, see* and *child*). Six clusters are located in the frontal lobe: right superior frontal (BA10: 33 voxels at $T = 5.16$, p <.5), right middle frontal (BA9: 73 voxels at $T = 4.20$), right superior frontal (BA8: 37 voxels at $T = 3.84$), right anterior cingulate (BA24: 33 voxels at $T = 3.51$), left IFG *triangularis* (BA45: 120 voxels at $T = 3.36$) and left SMA (BA6: 24 voxels at $T = 2.91$). The right fusiform (BA18: 24 voxels at $T = 4.09$), left posterior cingulate (BA19: 16 voxels at $T = 3.80$), right angular (BA7: 25 voxels at $T = 3.27$) and left superior occipital (BA18: 17 voxels at $T = 3.22$) are also recruited. The frontal regions may be interpreted as phonological processing and/or WM activity. Dehaene (2009), in turn, considers the *pars triangularis* activation as semantic access. The recruitment of the angular area contributes to semantic aspects of written input processing (Stoeckel et al., 2009). As well, the recruitment of BAs 18 and 19 supports orthographical processes. It is relevant to highlight the fact that most of the areas elicited in this analysis are located in the RH, reflecting, once again, spillover of activation in the L2.

While reading in their L1, bilinguals reading words that are more frequent (such as *noite*, *família* and *ver*) yield, in the temporal lobe, activation the bilateral superior temporal area (LH, BA42: 23 voxels at $T = 4.30$, p <.5; RH, BA22: 48 voxels at $T = 3.94$), normally associated with phonological processes. In the parietal lobe, there is activation in the left-lateralized posterior cingulate (BA5: 25 voxels at $T = 4.70$), superior parietal (BA7: 19 voxels at $T = 3.97$) and angular (BA40: 17 voxels at $T = 3.74$). In the frontal lobe, left-lateralized areas are recruited: the superior frontal (BA10: 17 voxels at $T = 3.21$) and the orbitofrontal (BA11: 16 voxels at $T = 3.09$). These areas seem to be associated with phonological, imagery and semantic processes. It is crucial to note that the L1 recruits predominantly left-lateralized areas while the L2, right-lateralized ones.

In monolinguals, reading words that are more frequent elicits activation in the right supramarginal extending to the postcentral region (BA40, 12 voxels at $T = 3.56$, $p < .05$; and another cluster with 14 voxels at $T = 3.54$). As aforementioned, the supramarginal area is traditionally implicated in phonological processing (Stoeckel et al., 2009). On the other hand, less frequent words (such as *sobrevoar, machucado* and *barulhento*) engage a set of bilateral areas, as the superior temporal region (BA22: one cluster with 77 voxels at $T = 5.33$, $p < .05$; and another cluster with 10 voxels at $T = 2.94$), normally associated with the conversion of orthographical information into speech code. A cluster in the left fusiform (BA37: 10 voxels at T = 4.26) is recruited reflecting orthographical processes. In the parietal lobe, only left-lateralized areas are involved: precuneus (BA7: 10 voxels at T = 5.00), superior parietal (BA7: 18 voxels at T = 3.46) and inferior parietal IPS (BA7: 11 voxels at T = 2.81), regions habitually implicated in visuo-spatial imagery and episodic memory retrieval (Cavanna & Trimble, 2006). In the frontal lobe, the majority of voxels are located in the RH: SMA (BA6: 10 voxels at T = 3.27) and middle frontal (BA9: 10 voxels at T = 3.21), but a cluster is located in the left IFG *pars orbitalis* (BA47: 17 voxels at T = 3.80). Frontal areas seem to be recruited for phonological processes, and according to Jobard and colleagues (2011), the *pars orbitalis* may be associated with semantic processing. As well, the right-hemisphere areas are probably recruited in the face of increased demands for the comprehension and maintenance of less frequent words.

In short, the answer to our fifth research question *Do word length and lexical frequency have an effect on brain activation of bilinguals and monolinguals?* is in accordance with the proposed hypothesis. Our lexical frequency findings seem to be in line with the literature about the routes employed for verbal written input processing. It is suggested that Portuguese, with a more transparent orthographic system, makes more use of the phonological route (or grapho-phonological route) whereas English, with its opaque orthography, employs more recurrently the lexico-semantic route (Palesu et al., 2000). Such an observation does not mean that Portuguese only uses the phonological route and English only the lexico-semantic route. Readers use both routes, in parallel, to mediate semantic access (Dehaene, 2009). As in the stimuli for the present study it was not our objective to manipulate word frequency, we have little variability in the sample of simple sentences. Possibly, it is the reason why we did not get clear-cut results as the literature previews. Word length analysis results support research findings that locate word length effects in the visual- and subarticulation-related areas. Essentially, our results in this analysis seem to corroborate the idea that the L2 engages a more distributed network of areas than the L1 does.

In a nutshell, our findings add support to the literature about bilingual and monolingual language comprehension by our analysis conducted at the word and sentence levels. The L2 seems to present a more anterior representation than the L1 as well as it seems to recruit additional voxels in adjacent areas and additional areas in the right hemisphere. For reading comprehension in bilinguals, the L1 engages a set of predominantly left-hemisphere areas while the L2 involves a more bilateral representation with spreading activation to the RH. We assume that the differences are due to the processing requirements of the bilingual brain. Despite such differences, both languages present a high degree of overlap in the brain areas recruited for the processing of sentences. Such overlap may indicate that activation for both languages converge. As regards monolinguals and bilinguals reading in Portuguese, a more complex set of areas was found in bilinguals, indicating that bilinguals engage the phonological network more than monolinguals reading the L1. Such a result may be suggesting that being a bilingual changes the way individuals process their L1. In the semantic neural identification analysis, our results suggest that the commonalities in the brain representation of the L1 and the L2 in bilinguals allows for successful decoding of sentences. In addition, the inclusion in our model of neurosemantic cuboids derived from three independent English monolingual subjects allowed the prediction of monolinguals and bilinguals reading in Portuguese. Therefore, such results pave the way for new studies by suggesting that there are common neural areas involved in the representation of different languages and cultures. Our cross-language findings revealed that training the data in the L2 and testing in the L1 resulted in higher rank accuracies, probably reflecting the fact that the L2 recruited more areas than the L1, and thus allowing the algorithm to learn from a *greater* neural space. As regards the effects of individual differences, word length and lexical frequency, the results seem to converge. Higher proficient and higher WMC readers seem to be more efficient in the recruitment of areas since they use less neuronal cortical tissue than lower proficient and lower WMC readers, who rely more on RH areas and recruit additional ones in the LH involved in visual, phonological and semantic processing. Word length effects are observed in visual and articulatory areas. Lexical frequency results suggest that the L1 relies more on left-hemispheric areas and more on the grapho-phonological route, while the L2 relies more on right-hemispheric areas and more on visual areas, probably reflecting the lexico-semantic route. As a whole, results seem to converge. In what follows, the chapter entitled final remarks recaps the objectives, research questions, hypotheses and findings of the present study as well as presents the limitations of the study and suggestions for further research.

CHAPTER 6
FINAL REMARKS, LIMITATIONS AND SUGGESTIONS FOR FURTHER RESEARCH

It is good to have an end to journey towards;
but it is the journey that matters, in the end.
(LeGuin, 1969, p.268)

In the present chapter, the general objectives, research questions, hypotheses and findings are addressed. Subsequently, the limitations of the study are presented as well as the directions for further research.

6.1 FINAL REMARKS

The present dissertation had as main objective to investigate the monolingual and bilingual brains and their neuroanatomical response to the processing of written sentences. More specifically, (1) it sought to explore whether and to what extent Portuguese and English are represented and processed in the same areas of the brain in late bilinguals; (2) whether Portuguese was represented and processed in same brain areas in bilinguals and monolinguals; (3) whether the semantic neural representation of sentences in one language could be identified based on the brain activation for the same sentences in another language; (4) whether individual differences, namely proficiency in the second language and working memory capacity modulated activation in bilinguals and whether working memory capacity modulated activation in monolinguals; and (5), whether word length and lexical frequency had an effect on brain activation. In order to reach such goals, an experiment was designed and for each specific objective, a research question and a hypothesis were generated. A summary of the main findings of this investigation is presented next:

Finding 1: Our hypothesis that the same brain regions would be recruited for the processing of L1 and L2 sentences in bilinguals (Chee et al., 1999; Illes et al., 1999; Isel et al., 2010) was confirmed. The late bilingual brain employed overlapping areas for the processing of the two languages (Chee et al., 1999; Isel et al., 2010; Paradis, 2004; Buchweitz, 2006; among many others).

Finding 2: Despite the high degree of overlap, bilinguals relied on a more widely distributed set of areas when processing the L2 and these additional areas were typically located in the right hemisphere (Marian et al., 2003; Hernandez et al., 2015; to mention some). As English presents a deeper orthography (than Portuguese), it resorts to more bilateral activation (dynamic spillover of activation of Prat et al., 2011), mainly in visual areas responsible for word recognition and orthographic processes (Buchweitz et al., 2012). In addition, higher levels of frontal activity, particularly in the SMA and the precentral region were found for processing the L2 than the L1 (Buchweitz, 2006; Dehaene et al., 1997). These additional areas are believed to reflect additional cognitive processes of reading in a second language. In the language difference analysis, no additional voxels were found the processing of L1-L2, and for the processing of L2-L1, only a small cluster in the right middle occipital region was found, close to the angular gyrus. Such result seemed to hold the interpretation that the L2 resorts to more right hemisphere activation (spillover of activation from Prat et al. (2011)). As well, this analysis seemed to corroborate the first finding that brain activation converges, overlaps for the processing of both languages.

<u>Finding 3:</u> Conceptual knowledge seemed to be organized over a widely distributed complex network of areas in the bilingual brain (Marian et al., 2003; Buchweitz & Prat, 2013) and differences between the two languages seemed to reflect processing requirements. Our results provide support to the claim that bilingual's languages are stored in memory in a shared system of representation (Dufour & Kroll, 1995; Bialystok et al., 2009).

<u>Finding 4:</u> Bilinguals engaged a more complex network of areas even to process their L1 in comparison to monolinguals (Kovelman et al., 2008; Parker Jones et al., 2012; Bialystok, 2011). L1 processing in bilinguals engaged more cortical areas for processing the phonological and semantic aspects of the L1 (Bolger et al., 2005). Additionally, the bilingual brain spread neural activation to right-lateralized regions (Prat et al., 2007). Such a result may suggest that being a bilingual changes the way individuals process their L1 (Bialystok et al., 2009).

<u>Finding 5:</u> The commonalities in the brain representations of words within and across languages were sufficient to allow the successful decoding of sentences. The present study was the first to investigate sentences and the first to recruit bilinguals and monolinguals for the same study. Our model generated reasonable accurate predictions of the neural representation of words based on simple addition of words, semantic features and semantic cuboids derived from an independent study.

<u>Finding 6:</u> Higher degrees of proficiency in the L2 engaged left superior temporal regions, while lower levels of proficiency recruited the right middle frontal, right caudate and left cerebellum (Wartenburger

et al., 2003). Bilinguals that are more proficient employed the *usual* route for comprehension by integrating the incoming words into a semantically based representation (Ferstl, 2007). In turn, lower proficient bilinguals resorted to predominantly right-lateralized areas (spillover of activation) to perform the same processes higher proficient bilinguals execute naturally (Perani et al., 1998).

Finding 7: In bilinguals, higher WMC modulated activation in the left superior orbitofrontal cortex, an area traditionally associated with the process of encoding new information (Frey & Petrides, 2000). Lower WMC modulated activity in a set of bilateral areas involved in visual, phonological and semantic processing (Jobard et al., 2005). Besides employing right-lateralized, lower WMC readers may be relying on less proficient processes to decode written input than higher WMC bilingual readers.

Finding 8: In monolinguals, higher WMC modulated activity in the right supramarginal region. The area is traditionally implicated in the phonological processing of language (Price, 1998; Stoeckel et al., 2009) and the recruitment of the right-hemisphere region is probably a reflection of the *spillover of activation*. Lower WMC modulated activation only in three areas: the left superior temporal, the left middle temporal and the right parahippocampal region. Such areas are associated with semantic and phonological processing (Price, 2010). Comparing bilingual and monolingual results, it is possible to infer that the bilingual experience of managing two active language systems possibly resulted in enhanced executive control (Bialystok et al., 2009; Grosjean, 2012). Lower WMC monolinguals recruited areas associated with semantic and phonological processing, while lower WMC bilinguals engaged a set of regions traditionally implicated in visual, phonological and semantic processing.

Finding 9: Word length effects were encountered in the traditional visual regions (Just et al., 2010; Wehbe et al., 2014) and in areas reflecting subarticulation processes (Mechelli et al., 2000). Lexical frequency effects were found in the traditional regions typically associated with phonological, semantic and orthographical processes (Jobart et al., 2005). Reflecting the spillover of activation (Prat & Just, 2011), the L2 recruited more right-lateralized regions whereas the L1, more left-lateralized regions. Our readers used the grapho-phonological and the lexico-semantic routes in parallel to mediate semantic access (Dehaene, 2009). However, readers tended to employ more the phonological route while reading in Portuguese and more the lexical route while reading in English (Palesu et al., 2000).

All in all, the results of this investigation add support to the literature that language processing requires much more than the *traditional language areas* (Bookheimer, 2002) as well as that the semantic level is shared among languages in monolinguals and bilinguals. The L1 representation and processing is more left-lateralized while the L2 receives more contribution from the right hemisphere (Buchweitz et al., 2012). Language processing in bilinguals and monolinguals require the participation of a widespread network of areas, with clusters of voxels being recruited from the four lobes, subcortical and cerebellar regions. The major innovation of this study relies on being able to successfully decode sentences cross language. Nevertheless, the present work suffered from a number of limitations and further research is needed to investigate language representation and processing in monolinguals and bilinguals.

Though this dissertation did not aim at establishing pedagogical implications, I believe that a better understanding of the bilingual brain affords contributions to the understanding of the mechanisms underlying the exceptional ability to process written input in two different languages. As well, by comparing the brains of bilinguals and monolinguals processing their L1, I believe that this study has contributed to the area with empirical data that helps scholars to understand how reading comprehension processes differ in the brains of monolinguals compared to the brains of proficient bilinguals.

6.2 LIMITATIONS OF THE STUDY AND SUGGESTIONS FOR FURTHER RESEARCH

Due to the nature of this study, the results gathered are to be seen as suggestive rather than conclusive. Despite the fact that it has been methodologically and theoretically driven by the literature in the field, the present investigation suffered from several limitations, which are pointed out. Suggestions for further research can be found in each of the presented limitations.

<u>Sample size:</u> Although our sample size was similar to those reported in other fMRI studies, “we acknowledge that a bigger sample would provide more detection power and, therefore, more reliable results” (Palomar-García et al., 2015, p.43). Conducting an fMRI experiment requires infrastructure and funding resources, due to the necessary machinery and personnel as well as to the scanner-session costs.

Different levels of proficiency and age of acquisition: Having a group of early bilinguals and/or a group of low proficient readers would have been interesting to compare to the group of fluent late bilinguals here investigated as done by Wartenburger and colleagues (2003) and Isel and colleagues (2010). Not being able to scan early bilinguals or different levels of proficiency may be viewed as a strength, as age of acquisition and proficiency were controlled successfully with a cross-sectional assessment of the proficiency participants exhibited at the time of the study.

Stimuli: The fact that our study made use of simple, short, everyday sentences can be considered a strength in an area where the overwhelming amount of studies are conducted at the word level. Nonetheless, it would have been interesting to present complex sentences; to manipulate sentence difficulty to observe the effects of task demands (Hasegawa et al., 2002); to use short paragraphs (Tomitch et al., 2008) or even larger stretches of discourse (Ferstl, 2007). In addition, several studies have been using concrete nouns (Buchweitz et al., 2012; Correia et al., 2014) to investigate language processing, the field calls for the investigation of stimuli with more abstract and culturally shaped concepts.

Use of other neuroimaging techniques: It would have been interesting to study monolinguals and bilinguals processing sentences with fMRI and DTI (diffusion-tensor imaging) to assess the structure of white matter tracts of the brain as Pliatsikas and colleagues (2015) did. As well, testing for differences in the density of gray and white matter between monolinguals and bilinguals might reveal the structural plasticity in the bilingual brain (Mechelli et al., 2004).

Anterior/posterior language representation: In the present study, we suggested that the L2 may be represented in the brain more anteriorly than the L1. This interpretation may be valid because the frontal lobes are evolutionarily the most recent part of the human brain, and during development, maturation happens in a back to front fashion. Taking into consideration Prat and Just's (2011) concept of neural adaptability, one may reason that the brain dynamically adapts itself to the cognitive demands of the tasks. Therefore, it may be possible to affirm that the L2, in late bilinguals, as a later learned language than the L1, is represented more anteriorly than the L1. At this point, this is merely an interpretation, more studies are needed to confirm or refute this viewpoint.

Semantic neural representation: Although this study presented several advances for the decoding of concepts in the context of sentences, the field calls for more studies by developing new models, methods and by testing new pairs of languages. It is believed that this study has paved the way for new studies by suggesting that there are common neural areas involved in the representation of words in the context of sentences in different languages and cultures.

As bilinguals represent such a hybrid population (Grosjean, 2012), many other factors are involved in modulating neural activity. Therefore, it is believed that there is a lot of room for new investigations, in Buchweitz's words (2006, p.72)

> it appears that not only is there room for more investigation in the area, but also that the study of bilinguals with neuroimaging has proven a fruitful testbed for language studies. These studies may afford new insights into how bilinguals, or language learners, cognitively respond to a second language, and afford evidence for the modeling of bilingual comprehension.

All in all, these limitations and suggestions are, by all means, not conclusive. It is important to consider that some of the suggestions raised in this work may be already under investigation, for the reason that new neuroimaging studies are published every month in well-known journals and presented in conferences all over the world. And despite the shortcomings, it is believed that the present study has contributed to enlighten, at least a bit, the understanding of how the monolingual and the bilingual brains respond to the processing of written sentences.

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APPENDIX A

A1: PET studies of brain activation patterns in bilinguals

Study	Participants	Measure of proficiency	Objectives	Task	Analyses	Main results
Klein et al. (1995)	12 English-French late fluent bilinguals (AoA: after 5 years old)	Tests that required generation of synonyms in L2, translating from L1 to L2, & providing a verbal description of the test room	To investigate whether phonological & semantic word-generation activate similar regions & whether the same neural substrates subserve L1 & L2	Production of one-word answers to auditory stimuli in 3 tasks: rhyme generation (phonological cues); synonym generation (semantic search); & translation (access to a semantic representation in L1 or L2) & word repetition as control	Group average, subtraction	Common neural substrates (no RH activation); left IFG is activated irrespective of whether the search is guided by phonological or semantic cues; greater activation in the left putamen in L2; more activation for generation than for repetition; no difference in frontal regions between languages
Perani et al. (1996)	9 Italian-English late bilinguals (AoA: after 7 years old) with moderate fluency	Word translation & sentence comprehension tests	To investigate whether activation patterns differ for L1 vs. L2, or for an unknown language (Japanese)	Listen passively to stories in L1, L2 & an unknown L3	Group average, subtraction	Activation overlap across L2 & L3; larger focus of activation in L1 relative to the L2 & L3
Perani et al. (1998)	9 Italian-English late fluent bilinguals (AoA: after 10 years old) 12 Spanish-Catalan early bilinguals	Word translation task with 3 lists: high-frequent, medium-frequent & low-frequent words	To investigate whether listening activation patterns differ for L1 vs. L2 in early & late bilinguals	Listen passively to stories in L1 & L2	Group average, subtraction	Activation overlap but late fluent bilinguals more bilateral areas than the late less fluent bilinguals in the 1996 study. Late bilinguals: no difference between L1 & L2; Early bilinguals: greater R mid temporal gyrus for L1 & greater R hippocampal & superior parietal lobules for L2
Klein et al. (1999)	7 Mandarin-English late fluent bilinguals (AoA: 12)	Description of pictures in L1 & L2 (fluency rated by a linguist; WAIS-R vocabulary subtest in English	To test whether linguistic distance (Mandarin-English) affects language patterns for L1 & L2	Production of one-word answers to auditory nouns: verb generation task; (word repetition as control task)	Group average, subtraction	Overlap in activation across languages (left frontal, parietal & temporal cortex); more activation for generation than for repetition

Acronyms: LH: left hemisphere; RH: right hemisphere; AoA: age of acquisition; ROI: regions of interest; LIFG: left inferior frontal gyrus; MTG: middle temporal gyrus; SPM, MEDx & SPM: statistical packages

A2: fMRI studies of brain activation patterns in bilinguals

Study	Participants	Measure of proficiency	Objectives	Task	Analyses	Main results
Dehaene et al. (1997)	8 French-English late bilinguals with moderate fluency (AoA: after 7)	Word translation & sentence comprehension tests	To investigate the cortical variability in the representation of language comprehension processes in L1 & L2	Listen to stories in their L1 or in their L2 & comprehension task	SPM96, subtractions, *t* tests, voxel counts	Consistent LH activation in L1; greater variability in L2
Kim et al. (1997)	6 early (AoA: infancy) & 6 late (AoA: after 11) bilinguals (from 10 different languages)	Not applicable - the authors justify that the participants had lived in the country of the L2 for some time	To investigate how multiple languages are represented in the human brain	Sentence-generation task: silent production of sentences that described events	Centroids, pixel counts within Broca's & Wernicke's areas, ANOVA (no info about the package)	Activation overlap in L1 & L2 for early bilinguals; late bilinguals showed spatial separation in Broca's
Chee et al. (1999)	9 Mandarin-English early fluent bilinguals (AoA: before 6)	Score higher than B+ in middle school examinations & 70% of accuracy or higher in the experimental task in both languages	To determine if differences in the surface features (orthography, phonology, & syntax) of different languages affect their cerebral organization at the sentence level	Read sentences in their L1 & L2: comprehension (true/false); (presentation of foreign script as control task)	MedX 2.11/3.0, subtractions, *t* tests, peak locations, voxel counts, SPSS8 (for behavioral data)	Activation overlap for L1 & L2, supporting the idea that concepts are directed accessed from the L2 in fluent bilinguals
Illes et al. (1999)	5 Spanish-English &3 English-Spanish late fluent bilinguals (AoA: after 10)	Self-reported ratings in reading, writing, speaking & comprehension	To examine whether semantic processes in L1 & L2 are mediated by a common neural system	Read words: semantic decision (concrete or abstract words) & nonsemantic decisions (letters in uppercase or lowercase)	SPM, subtractions, ROI analysis, *t* tests	Consistent LH activation overlap for both languages; some participants also showed RH activation for both languages

Hernandez et al. (2001)	6 Spanish-English early fluent bilinguals (AoA: before 5)	Boston Naming Test in L1 & L2	To examine the neural substrate of language switching	Covert naming between vs. within-language switching	SPM96, subtractions, ANOVA for behavioral data	LH activation overlap across languages, plus increased prefrontal activation for between-language switching
Nakada et al. (2001)	5 English-Japanese & 5 Japanese-English late highly literate bilinguals (AoA: after 11)	SAT scores (Scholastic Aptitude Test) in English & an equivalent in Japanese	To determine the neuroanatomic substrates employed in L1 reading, & the effect of L1 on the neurosubstrates involved in L2 reading	Read sentences in L1 & L2 (reading non-language stimuli as control task) – comprehension probes after the scanning session	SPM96, subtractions, *t* tests	L1 reading: activation overlap in left frontal areas; greater activation in inferior temporal regions for Japanese & bilateral lingual gyrus for English; L2 reading in both groups showed identical activation to L1 reading, suggesting that L1 impacts L2
Hasegawa et al. (2002)	10 Japanese-English late bilinguals with moderate fluency (AoA: after 12)	Language background questionnaire: self-assessment of proficiency	To examine the cortical substrates that support the comprehension of the L1 & the L2	Listen to sentences (easy & hard) & answered comprehension questions during scan	FIASCO, ROI analysis, voxel counts, ANOVA, subtractions, *t* tests	More activation for the L2, suggesting that more cognitive effort was required to process it; increase in task difficulty, increase in activation
Marian, Spivey & Hirsch (2003)	6 Russian-English late fluent bilinguals (AoA: 17)	No assessment reported in the paper	To compare the cortical areas activated during L1 & L2 processing	Read & listen to L1 & L2 words & nonwords	Subtractions, center-of-mass procedure	IFG active in phonological & lexical processing; STG active in phonological processing; L2 elicited greater activation than L1
Wartenburger et al. (2003)	Italian-German bilinguals: 11 early fluent (EAHP) 12 late fluent (LAHP) 9 late low proficient (LALP)	Proficiency tests (all the skills)	To clarify which factors (AoA & proficiency level: PL) might influence the cortical representation of grammatical & semantic judgments in L2	Read 180 short sentences (90 in each language), half were grammatically & semantically correct, the other half (46) contained either grammatical (23) or semantic (23)	SPM99, subtractions, *t* tests, non-parametric tests (behavioral data)	AoA affects the neuronal processing mechanisms of grammatical judgments more than PL; PL seems to play a larger role in determining the neuronal substrate for semantic processing

Tatsuno & Sakai (2005)	14 age 13 Japanese-English bilinguals (AoA: 12 – 8 months learning English) 15 age 19 Japanese-English bilinguals (AoA: 12 – 6 years learning English)	Age 13 group: received 2 months of classroom training in the English past tense; Age 19: had already learnt it	To clarify the relative contributions of age, proficiency level, language task demands, & task performance to modulating activations in the left prefrontal cortex (developmental process in mastering an L2)	Silent word reading/production: 48 verbs (regular & irregular) in English & in Japanese (hiragana & kanji writing systems) in tasks of verb matching & past tense use	SPM99, subtractions, correlations, *t* tests	Lower activation in the dorsal triangular part of the IFG & in the triangular & orbital parts of the left IFG for the irregular past tense in higher proficient (older) participants; no activation for regular past in higher proficient participants; more activation in these regions for age 13 group in Japanese (L1)
Buchweitz (2006)	12 Portuguese-English late fluent bilinguals (mean AoA: 13)	Participants answered a language background questionnaire, but they had previously taken the TOEFL test	To investigate bilingual comprehension in two modalities: reading & listening as well as the involvement of WMC in comprehension	Listen to & read L1 & L2 statements (sentences) about general world knowledge, & comprehension task	SPM99, subtractions, ROI analysis, *t* tests	Comparable L1 & L2 activation; L2 additional premotor activation; reading recruits more LH areas than listening + VWFA
Crinion et al. (2006)	**PET:** 11 fluent late German-English bilinguals; **fMRI:** 14 fluent late German-English bilinguals 10 fluent late Japanese-English bilinguals	English Voc. Test; New Adult Reading Test (NART) (knowledge of phonemes & irregularly spelled words); Graded Naming Test (GNT) & knowledge of low frequency words	To examine how the bilingual brain distinguishes & controls which language is in use	Read word pairs: ignore the 1st & make a semantic decision based on the meaning of the second target; task about decision of symbols as a baseline	SPM2, subtractions, *t* tests, ANOVA	Activation overlap irrespective of which language is presented; left caudate: sensitive to changes in the language or word meaning, suggesting a universal role in monitoring & controlling the language in use
Meschyan & Hernandez (2006)	12 Spanish-English early proficient bilinguals	Boston Naming Test (vocabulary); word-reading task; self-assessment in Spanish & English language abilities => participants were more proficient in their L2	To examine how language proficiency & orthographic transparency (letter-sound-mapping consistency) modulate neural activity during bilingual single word reading	Silent reading of 48 words in English & 48 in Spanish	SPM99, subtractions, ANOVA	L1 (less practiced), requires greater articulatory motor effort (slower reading rates); more transparent L1 words yielded greater activity in STG; opaque L2 words, more activity in visual areas

Yokoyama et al. (2006)	36 Japanese-English late bilinguals with moderate fluency	English Language Proficiency test: the test has seven grades: from 1 (lowest) to 5 (highest). At pre-level 2, speakers are assumed to have a sufficient level of comprehension & production to participate in daily life	To investigate whether late bilinguals process structurally complex sentences in L1 & L2 in different cortical networks	Read 72 sentences phrase by phrase: judge whether or not the presented sentences were semantically plausible	SPM99, subtractions, ANCOVA, ROI analysis	Overlap in areas for L1 & L2 processing; L1: passive sentences greater activation (than active sentences) in the LH pars triangularis, premotor area, &superior parietal lobule; in addition to AoA & L2 proficiency, differences in grammatical construction affect cortical representation
Saur et al. (2009)	12 German-French late bilinguals; 12 French-German late bilinguals; 12 German-French early bilinguals	2 multiple-choice proficiency tests	To examine whether AoA affects naturally occurring syntactic regularity at the sentence level, such as word order.	Listen to sentences: judge syntactical accuracy of the sentences	SPM2, subtractions, ANOVA, *t* tests,	Late bilinguals: L2 processing higher levels of activation mainly of the LIFG; early bilinguals: no difference; French as L1: higher activation for Verb-subject-order than German L1 speakers
Buchweitz et al. (2009b)	9 Japanese-English late bilinguals (AoA: mean of 26)	Language background questionnaire (self-ratings): intermediate level of proficiency	To investigate the brain activation associated with reading comprehension & different orthographies in two Japanese writing systems, & in English, as the L2	Read sentences: two-clause target sentences in English, & Japanese *hiragana* & *kanji* scripts; either negative or affirmative statements; single-clause probe to check for comprehension	SPM99, subtractions, *t* tests	*Kanji*: more activation in RH occipito-temporal lobe; *Hiragana:*: more activation for phonological processing; English: more activation in the IFG, medial frontal & angular gyri; Additional activation L2: increased demand for phon. proc.& verbal WM

Isel et al. (2010)	10 French-German early bilinguals (AoA: before 3) 10 French-German late bilinguals (AoA: 11)	Questionnaire assessing the amount of actual exposure to both languages in various domains; & a translation test (L2 to L1) applied post scanning	To test the assumption that the mental representation of lexical knowledge in L2 is affected by neural maturation	Read 120 concrete words (nouns): semantic categorization task	SPM2, subtractions, *t* tests, ANOVA	L1 & L2 share a common space of conceptual representations for early & for late bilinguals; differentiated patterns of neural priming for both amplitude & localization as a function of AoA; age of exposition might have an effect on the cortical organization of the mental lexicon of the L2
Yang, Tan & Li (2011)	16 Chinese-English late bilinguals (AoA: 12)	Language proficiency questionnaire (self-assessment)	To investigate the lexical representation of nouns & verbs in the late bilingual brain	Silent reading of words: lexical decision task (nonwords as control)	SPM8, subtractions, *t* tests, ANOVA	Largely overlapping neural networks, but bilinguals rely on a more widely distributed neural system in L2 than in L1: greater activation in RH regions: middle frontal, insula, angular gyrus & bilateral superior parietal lobes
Buchweitz et al. (2012)	11 Portuguese-English late fluent bilinguals	Participants answered a language background questionnaire, but they had previously taken the TOEFL test	To identify the neural representation of a noun's meaning in one language based on the neural representation of that same noun in another language	Passive reading of 14 words from two categories: tools & dwellings	SPM2, subtractions, *t* tests, MVPA, machine learning techniques	Remarkable similar brain activation for L1 & L2, thus enabling the identification of the neural representation of the same word in another language

Jamal et al. (2012)	12 Spanish–English early fluent bilinguals (AoA: before 6)	A battery of standard neuropsychological tests to measure single-word reading skills in English & in Spanish as well as other cognitive skills	To investigate single-word processing in Spanish & in English in proficient early Spanish-English bilinguals matched in skill level in both languages	Silent single-word reading: decide whether 80 words have tall letters; & 80 false font strings (80 for each language, in total)	MEDx, SPM99, subtractions, *t* tests	L1: LIFG & left middle temporal gyri; L2: LIFG, middle frontal & fusiform gyri extending to inferior temporal gyrus & the right middle temporal gyrus extending into superior temporal sulcus; explanation: English as an orthographically deep language
Correia et al. (2014)	10 Dutch-English bilinguals (no information about AoA)	Proficiency in both languages was assessed with two vocabulary tests (40 frequent words & 20 nonwords)	To investigate the semantic representation of spoken words at the fine-grained level of within-category distinction & across-language generalization	Listen to single words: 4 animals nouns & 3 inanimate objects in each language; task: detect non-animal target nouns	Subtractions, MVPA (no information about the statistical package used)	Semantic-conceptual knowledge organized in language-independent form in focal regions of the cortex: STG, medial anterior temporal lobe, anterior insula in the RH; anterior temporal lobe, angular & postcentral gyri in the LH; & bilateral occipital cortex; ATL as a semantic hub
Hernandez, Woods & Bradley (2015)	20 adults (18-26 age) & 21 children (8-13 age) early Spanish-English bilinguals (AoA: before 9)	Use of the languages + Woodcock Language Proficiency Battery + Picture Vocabulary in English & Spanish + Listening Comprehension in English & Spanish	To examine the neural correlates of lexical processing in early L2 learners during the transition from L1 dominance in childhood to L2 dominance in adulthood	Silent single word reading: 120 nouns (60 in each language); reading accuracy after scanning	SPM8, subtractions, ANOVA	Both groups: similar network of LH areas, but adults recruited more the bilateral MTG & were more proficient in L2

Acronyms: LH: left hemisphere; RH: right hemisphere; AoA: age of acquisition; ROI: regions of interest; LIFG: left inferior frontal gyrus; MTG: middle temporal gyrus; SPM, MEDx & SPM: statistical packages

A3: Bilingual and monolingual brains compared

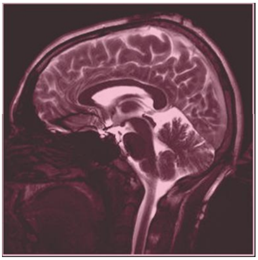
Study	Participants	Measure of proficiency	Objectives	Task	Analyses	Main results
Kovelman, Baker & Petitto (2008)	10 English monolinguals (no exposure to other languages until age 7); 11 Spanish-English early bilinguals	Bilingual language background & use; language competence & expressive Proficiency (LCEP) test	To investigate whether a bilingual brain, even when a bilingual is using only one language, processes linguistic information in the same manner as a monolingual brain	Read 40 sentences (mono: English; bi: the same 40 in English & additional 40 in Spanish); judge the plausibility	SPM99, subtractions, ANOVA, ROI analysis	Bilinguals & monolinguals activated the same brain areas; bilinguals had increased activation in the left inferior frontal cortex (within BA 44 & 45)
Parker-Jones et al. (2011)	36 English monolinguals 10 heterogeneous bilinguals (L1: German, Italian, Dutch or Czech; L2: English) 10 Greek-English bilinguals (only scanned in English) 11 Greek-English bilinguals (scanned in both languages)	Lexical decision test (Psycholinguistic Assessment of Language Processing in Aphasia-PALPA); letter & category fluency tests; color-word Stroop task	To investigate whether brain activation differed for bilinguals & monolinguals when bilinguals are tested in a single language context, either in their native language or in a foreign language (but not both on the same day)	Picture-naming; silent word reading; lexical-semantic decision tasks	SPM5, subtractions, ANOVA	Bilinguals showed more activation in 6 left-lateralized regions: planum temporale, dorsal precentral, STG, pars opercularis, pars triangularis & insula; increased work in brain areas that support monolingual word processing
Palomar-García et al. (2015)	21 Spanish monolinguals 23 Spanish-Catalan early fluent bilinguals	Interview about their daily use & exposure to both languages in a variety of contexts, their personal & family language history; questionnaire about language history (AoA, use, preference, self-reported proficiency)	To explore the brain activity of a group of early & high-proficient Spanish–Catalan bilinguals to that of a group of Spanish monolinguals processing their native language (Spanish) - no involvement of bilinguals' L2 during the session.	Passive listening of words & picture-naming	SPM8, subtractions, *t* tests, ANOVA	Differences appeared only in the picture-naming task: the bilingual brain reduces the participation of the left MTG, but recruits areas in the medial parietal region & widely spreads neural activation to the right STG; the 1st study to show that monolinguals use more posterior-related brain areas than bilinguals.

Acronyms: LH: left hemisphere; RH: right hemisphere; AoA: age of acquisition; ROI: regions of interest; LIFG: left inferior frontal gyrus; MTG: middle temporal gyrus; SPM, MEDx & SPM: statistical packages

APPENDIX B

B1: Recruitment flyers (posters) in English

Want a picture of your brain?



Participate in an fMRI study and get $75 (plus a possible $15 bonus) and a picture of your brain!

Study Includes:

- Thinking about simple sentences during an fMRI scan
- fMRI Scan and practice/debriefing
- Pencil and Paper Tasks

We are looking for staff and students who are:

- Between the ages of 18-35
- Native Portuguese speakers who speak English as a second language or Monolingual Portuguese speakers
- Right Handed
- Good health

For more information about study times and to see if you qualify, email Alex-7@andrew.cmu.edu

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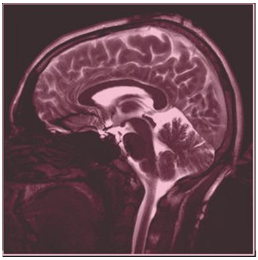
B2: Recruitment flyers (posters) in Portuguese

Gostaria de ter uma foto do seu cérebro?



Participe de um estudo com fMRI e ganhe U$75
(mais um possível bônus de U$15) e uma foto do seu cérebro!

O estudo inclui:

- Pensar em frases simples durante uma sessão de fMRI
- Sessão de fMRI com prática e questionário
- Tarefas envolvendo lápis e papel

Estamos à procura de funcionários e estudantes universitários que:

- Tenham entre 18-35 anos
- Sejam falantes nativos de português e falem inglês como segunda língua ou falantes monolíngues de português
- Sejam destros
- Tenham boa saúde

Para maiores informações, escreva um e-mail para Alex-7@andrew.cmu.edu

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APPENDIX C

C1: fMRI FAQ for bilinguals

fMRI Scan FAQ

CCBI – Center for Cognitive Brain Imaging

1. What is MRI?

Magnetic resonance imaging (MRI) is a non-invasive technique that provides high-quality pictures of hard body tissues (such as bone) and of soft body tissues (such as the brain). MRI technology uses magnets, radio waves, and computers to produce its images. It does **not** require surgery, harmful dyes, X-rays, or any other kind of ionizing radiation. Because of its non-invasive nature, it is often used in medical imaging. There are typically no unpleasant sensations associated with an MRI scan.

2. What is fMRI?

In functional MRI, high-quality pictures of the brain are taken to study brain activity. The pictures are taken at a steady rate so that changes in brain activity over time can be measured. In fMRI, it is important for the participant to lie perfectly still so that the pictures can be easily lined up with each other and compared against each other.

3. How does fMRI measure brain activity?

fMRI tracks changes in brain activity by observing the magnetic resonance characteristics of blood flow in the brain. One component of blood is the oxygen-carrying protein called hemoglobin. Hemoglobin has different magnetic properties depending on whether oxygen is currently attached or not. When brain activity increases or decreases in a certain area, the local blood flow and levels of oxygenation change, which alters the magnetic resonance of blood in that local area. fMRI is sensitive enough to detect these small changes.

4. Is the fMRI scanner safe?

The fMRI scanner is safe as long as you have no metal in your body. Such metal could include a cardiac pacemaker, aneurysm clip, cochlear implant, IUD, shrapnel, non-removable body piercing, neurostimulator, metal fragments in the eyes, or any other metal (except for dental fillings, which are okay). Also, you cannot bring any metal objects into the scanner with you. You will be carefully screened for metal in your body or on your person; any metal possessions will be stored in a locker during your scan. In addition, some participants should not participate due to discomfort; these are persons who may be pregnant, and persons who do not fit well into the scanner due to being over 300 pounds or due to having very broad shoulders.

5. What is it like to be in an fMRI scanner?

The fMRI scanner is a hollow tube. You will be placed on a sliding bed, and a helmet consisting of widely spaced bars will rest over your head area. There is padding under your head to help keep your head perfectly still and comfortable. The bed will slide partway into the scanner until your upper body is positioned in the tube. Occasionally people feel claustrophobic in the scanner; if this is a problem for you, the study will be ended early. You can quit at any time during the study.

6. What will I do in the scanner?

You will be lying down in the scanner and watching a computer screen through a small mirror positioned on the fMRI helmet. Simple sentences will be presented to you in chunks, like “The day / was / beautiful” and you will be asked to <u>think about the properties of the words while they appear on the screen</u>. Some words and sentences will be presented more than once and you should consistently think about the same set of properties. When an X appears on the screen, you should clear up your mind until the next words appear on the screen. And last but not less important, you will be asked to hold still throughout the scan.

7. What side effects or sensations may be experienced while in the scanner?

The scanner produces a variety of noises while in operation; some of them are louder than others. You will be given ear protection (earplugs or noise-canceling headphones) to dampen the noises and provide you with greater comfort. Still, some participants report feeling distracted by the louder sounds of the scanner. If you have particularly sensitive hearing, please alert the scan technologist so s/he can offer you both earplugs and noise-attenuating headphones.

If you wear tattoos, makeup, or a nicotine patch, you may feel a slight warming sensation on your skin where these items are located. If this becomes uncomfortable, please let the scan technologist know.

Because participants need to hold very still in the scanner, occasionally they report developing minor body aches, stiffness, headaches, or limbs starting to fall asleep. It is important that you try to get <u>as comfortable as possible</u> before going into the scanner in order to try to minimize these effects.

In addition, because the upper body is placed within a narrow tube, some participants experience claustrophobia. Moreover, due to the narrow space, loud noises, or because of trying to keep still, a few report that their breathing becomes shallower. We encourage all participants to relax and breathe normally (while trying to keep the head as still as possible). If you feel any kinds of discomfort during your scan, please let the scan technologist know so s/he can reposition you if needed, or end the scan early.

8. Will researchers be present nearby during the fMRI scan?

The scan room is located adjacent to a control room. Experimenters typically sit in the control room during a scan, and they can see you through a window that connects the two rooms. Because your upper body will be inside a hollow tube, experimenters can see your lower body. There is also a mini-camera focused on your eyes so the experimenters can see whether you are awake or not during the scan. There will be a bilingual Portuguese/English researcher with you on all sessions.

9. Can I talk to the experimenters during the fMRI scan?

While you are in the scanner and the staff are in the control room, the staff will use an intercom at regular intervals between tasks to ask you how you're doing, and to let you know what's coming up next. At these times, let them know about any questions or concerns you have related to comfort, how well you can perceive the experimental stimuli in general, or anything else. If you have a concern that needs to go immediately to the staff (due to discomfort or any problems with the experimental stimuli being presented during a task), then you will need to alert them by squeezing the ball that will be placed on your stomach during the scan. The scanner is noisy when in operation, but by squeezing the ball, an alarm will be sounded in the control room. Immediately, researchers will either talk to you over the intercom, or walk into the scanner room to talk with you directly. Staff will not be able to hear you talk while the scanner is running, which is why you'll need to use the squeeze ball to get their attention so they can turn off the scanner noise.

10. What should I do if I notice an apparent problem with the stimuli during the scan?

If the screen showing the stimuli appears to go dark for a long while, then it's possible that the screen settings need to be adjusted. You should alert the scan technologist by pressing the squeeze ball located on your stomach.

11. Can someone stay with me in the scan room during the scan?

If it would make you feel much more comfortable, a person who has undergone the same safety screening as you have can sit in the scan room during the scan. For example, one of our researchers can do this. You will not be able to see this person, but he or she can rest a hand on your foot (etc.) to make you aware of his or her presence if that would make you feel more comfortable.

12. Are there any medications, foods, liquids, or other such items I should avoid before my scan day?

Avoid caffeine on the day of your scan because it may make you prone to moving in the scanner, and because it affects the way your brain functions. You will also need to avoid certain kinds of medications that may make you feel stimulated or drowsy.

Please consult us about medications before your scan if you take any regularly, or if you plan to take them on the day before, or of, your scan. If you take certain medications on the day of your scan, we may not be able to scan you on that day. Also, avoid coffee and other diuretics that may require you urinate more often because you are requested not to use the restroom for the duration of the scan (60 minutes).

13. What advice should I follow for a successful scan?

Make sure to get plenty of sleep the night before the scan, so you will be alert for all the tasks in the scanner. You should avoid things that make you stimulated or drowsy, such as caffeine and certain medications (ask us for details). You should take the opportunity to visit the restroom right before the scan. In addition, you might want to get a small drink of water to make sure you will not feel thirsty during the scan. Finally, during your scan just focus on performing the tasks as instructed, and keep your body (especially your head) as still as possible. Try your best to stay focused on the activities the entire time you are in the scanner.

14. What if I have to cough/sneeze/yawn while I'm in the scanner?

Try not to cough, sneeze, or yawn if you can avoid it. However, if you really have to and it will be of limited duration, wait until a break between tasks (such as when the researcher talks to you on the intercom) and then go ahead but try to keep your head as still as possible. If you find that you actually have a fit of coughing/sneezing/yawning (that would incur a lot of head motion) and you need to exit the scanner, then just press the squeeze ball to alert the scan technologists of your need.

15. Should I scan on a day when I have a cold or allergies with head or chest congestion?

It's best to reschedule your scan if you have head or chest congestion, or if you're otherwise feeling ill. As soon as you realize you cannot make it for the scan, contact us to let us know. If you're feeling somewhat borderline (well enough to want to try, but still a little concerned), please contact us for advice as soon as possible before your scan. Do not take any cold medicines on the day of your scan.

16. Why do I have to lie very still in the scanner? Is there a safety issue involved?

You will be safe in the scanner as long as you have no metal, even if you move. However, if you are unable to lie sufficiently still in the scanner, we cannot properly align successive pictures of your brain to each other. Thus, we would not be able to use the data from a participant who moved a lot while in the scanner. It is for that reason that we give you the opportunity to lie in a mock scanner while tracking your head for motion in order to determine whether you can keep sufficiently still in the scanner to yield good data.

17. What are the exclusion criteria for scanning?

There are a few restrictions for participants in an fMRI research study. Because the MRI machine is a large magnet, people who have metal in their bodies may not participate. Such metal could include a cardiac pacemaker, aneurysm clip, cochlear implant, IUD, shrapnel, non-removable body piercing, neurostimulator, metal fragments in the eyes, or any other metal. Dental fillings are allowed. In addition, people who are pregnant, weigh over 300 lbs., or may be claustrophobic in the magnet should not participate due to discomfort. In this particular study, we are interested in scanning native speakers of Portuguese (18-35 years old) who speak English as a second language and are predominantly right-handers.

18. What kinds of clothing can be worn in the scanner?

Warm, comfortable, loose-fitting clothing should be worn. For example, sweatpants and a sweatshirt are ideal because they have no metal zippers, metal buttons, or other fittings. The scanner room can get cold. We have a blanket we can offer you, but it helps to dress warmly. Metal on clothing should be avoided (unless it's a small amount on your pants only). Please do not wear metal belts, underwire bras, clothing with metallic threads, or metal buttons or metal zippers on your shirt. If you wear pants or jeans having metal buttons, zippers, or rivets, then those are okay but only when on your pants.

19. Can jewelry, accessories, or other items be worn in the scanner?

No metal hair clips, jewelry, watches, rings, earrings, etc. can be worn. We will ask you to remove these before entering the scan room. Also, do not bring in any loose change, keys, cell phones, or other metallic items. In particular, credit cards and any other kind of card having a magnetic stripe should not be brought into the scan room, because they will be erased by the magnet in the scanner.

20. Can make-up be worn in the scanner?

Rarely, certain types of eye make-up (like eyeliners) contain tiny metallic particles that can prevent the capture of clear MR images, or that can become uncomfortably warm during the scan. If this happens, you will be asked to remove your make-up. You should avoid any make-up that sparkles or that you know has metallic content. Also, you might want to consider coming without make-up at all, to avoid having to remove it.

21. Can I participate in an fMRI scan if I am pregnant, or might be pregnant?

If you are a woman of childbearing age and you suspect you may be pregnant, a free pregnancy test will be administered to you before you will be allowed to participate. If you test positive for pregnancy, you will be excluded from the study due to possible discomfort.

22. Are glasses or contacts allowed in the scanner?

You can wear your contacts in the scanner. If you wear glasses, we will provide you with a substitute pair of plastic glasses that roughly match your prescription. Prescription strengths we can accommodate are -1 to -6 (for near-sighted folks) and +1 to +5 (for far-sighted folks). All glasses strengths are available in half-step increments.

23. Are permanent orthodontic braces or retainers allowed in the scanner?

If you have permanent braces or retainers, please alert us so we can check whether you will be eligible for scanning. There is no risk to you if you have these, but depending on the placement and extent of metal, their presence may cause artifacts in our pictures that would make them unusable to us. Generally, permanent retainers are okay as long as they are small, and as long as the metal is located on the front teeth (not on the back teeth). Please find out whether the metal in your orthodontic device is fully non-ferromagnetic or not, because that would also be helpful to us in determining your eligibility.

24. What kinds of ear protection are available?

Industrial-strength earplugs and noise-attenuating headphones are available to use as hearing protection. If your hearing is particularly sensitive, you can request that both kinds of protection be used simultaneously.

25. How long will my fMRI session last?

You will participate in two fMRI scanning sessions of 60 minutes each in two different days.

26. What will I have to do in this study? What will happen on the day of my scan?

As soon as you communicate the researcher your decision to participate, she will call/e-mail you and arrange the meetings as well as provide you with specific instructions as regards the place we will meet. On the first meeting, the researcher will read with you the consent form, you will complete a handedness questionnaire, and the researcher will explain in detail the task you will perform inside the fMRI scanner: think about the words and sentences and their meanings as they appear on a screen. You will practice the task and then, you will be taken to the mock scanner (simulator) so that you can have the opportunity to feel how the session in the real scanner will be. At this time, you should ask any remaining questions you may have about the procedure. You will go the room of the real scanner and you will be about one hour thinking about the meaning, the properties of the words and sentences presented to you in one of the languages: Portuguese or English. At the end, you will perform a recognition task, which involves recognizing the sentences you saw and

did not see inside the scanner, and complete a debriefing questionnaire. This session will last at about two hours.
On the second day, you will be asked to think about the meaning and properties of words and sentences in the other language, you will perform the recognition task and complete the debriefing questionnaire as in the first session. This session will last about two hours.
On the third and last day, you will perform two working memory tests, called the Reading Span Tests, one in English and one in Portuguese; you will answer one quick questionnaire about them; you will complete a language background questionnaire and will perform the reading part of a proficiency test in English. This session will last about two hours and there is no fMRI scanning.
During the three sessions, you will have opportunity the take breaks if you feel tired. You may be surprised with the number of questionnaires you will have to complete, but they are short and fast to answer and aim at providing the researcher with the information necessary to describe the group of participants and also information regarding how the participants felt performing the activities.

27. What should I do if I want to quit during the practice or the scan?

It's okay to take a break at any time if you need one, or to quit early if you need to. Alert the researchers immediately as soon as you decide you need a break or you need to quit. If you are in the scanner, then squeeze the ball to get the attention of the researchers.

If you have any doubt, be sure to ask the researcher personally or write to her.

C2: fMRI FAQ for monolinguals

Perguntas frequentes sobre fMRI (Ressonância magnética funcional)
CCBI – Center for Cognitive Brain Imaging

1. O que é ressonância magnética (do inglês: MRI)?

A ressonância magnética é uma técnica não-invasiva que fornece imagens em alta resolução de tecidos duros (como o osso) e de tecidos moles do corpo (como o cérebro). A tecnologia de ressonância magnética usa ímãs, ondas de rádio e computadores para produzir imagens. **Não** requer cirurgia, corantes nocivos, raios-X, ou qualquer outro tipo de radiação ionizante. Devido à sua natureza não-invasiva, é frequentemente usado em imageologia médica. Tipicamente **não** há sensações desagradáveis associadas a um exame de ressonância magnética.

2. O que é fMRI?

Na ressonância magnética funcional, imagens com alta resolução do cérebro são feitas para estudar a atividade cerebral. As imagens são feitas a uma velocidade constante de modo que mudanças na atividade cerebral ao longo do tempo podem ser medidas. Na ressonância magnética funcional, é importante que o participante fique totalmente parado durante a sessão para que as imagens possam ser facilmente alinhadas uma com a outra e comparadas umas com as outras.

3. Como se mede a atividade do cérebro com fMRI?

O fMRI controla as alterações na atividade cerebral observando as características de ressonância magnética do fluxo sanguíneo no cérebro. Um dos componentes do sangue é a proteína que transporta o oxigênio chamada hemoglobina. A hemoglobina tem diferentes propriedades magnéticas, dependendo se o oxigênio está contido nela ou não. Quando a atividade cerebral aumenta ou diminui em uma determinada área, o fluxo sanguíneo local muda, além dos níveis de oxigenação, o que altera a ressonância magnética de sangue nesse local. O fMRI é sensível o suficiente para detectar essas pequenas mudanças.

4. O fMRI é seguro?

<u>O scanner de fMRI é seguro, desde que você não tenha metal em seu corpo</u>. Por metal entende-se: aparelho nos dentes, marca-passo cardíaco, clipe de aneurisma, implante coclear, DIU, fragmentos de metal, body piercing não-removível, neuroestimulador, ou qualquer outro metal (obturações dentárias são permitidas). Além disso, você não pode trazer quaisquer objetos metálicos dentro do scanner com você. Será feita uma triagem para assegurar que você não tem metais em seu corpo ou com você; quaisquer bens metálicos serão armazenados em um armário durante a sessão. Além disso, algumas pessoas não devem participar: mulheres que possam estar grávidas e pessoas que não se encaixam bem no scanner por ter mais de 136 kg ou por ter ombros muito largos.

5. Como é estar em um scanner de fMRI?

O scanner de ressonância magnética é um tubo oco. Você será colocado em uma cama deslizante, e um capacete que consiste em barras espaçadas vai descansar sobre a área da sua cabeça. Colocaremos algumas espumas ao redor da sua cabeça para ajudar a manter a sua cabeça completamente imóvel e confortável. A cama vai deslizar parcialmente dentro do scanner até que a sua parte superior do corpo seja posicionada dentro do tubo. Às vezes as pessoas se sentem claustrofóbicas dentro do scanner. Para isso, faremos uma simulação para você ver como se sente. Lembre-se de que você pode desistir do estudo quando quiser.

6. O que eu vou fazer no scanner?

Você estará deitado no scanner observando uma tela de computador por meio de um pequeno espelho posicionado no capacete do fMRI. Frases simples serão apresentadas a você em partes, como "O dia / foi / bonito" e pediremos que você pense sobre o significado das palavras, as propriedades delas, enquanto elas aparecem na tela. Algumas palavras e frases serão apresentadas mais de uma vez e você deve sempre pensar sobre o mesmo conjunto de propriedades (ativar o mesmo significado cada vez que palavra/frase aparecer). Quando um X aparecer na tela, você deverá limpar a sua mente e tentar não pensar em nada até as próximas palavras aparecerem na tela. E por último, mas não menos importante, exige-se que você fique totalmente parado durante todo o tempo dentro do scanner.

7. Que efeitos colaterais ou sensações podem ser experimentadas enquanto eu estiver no scanner?

O scanner produz uma variedade de ruídos em funcionamento; alguns deles são mais altos que outros. Você receberá protetores de ouvido (tampões de ouvido industriais) para atenuar os ruídos e proporcionar maior conforto. Ainda assim, alguns participantes relatam se sentir distraídos com os sons mais altos do scanner. Se você tem audição particularmente sensível, por favor alerte o tecnólogo ou a pesquisadora que estará com você para ele(a) lhe oferecer tampões de ouvido e fones de ouvido com atenuação de ruído.

Se você tem tatuagens, ou estiver usando maquiagem, ou ainda um adesivo de nicotina, você pode sentir uma leve sensação de aquecimento em sua pele onde esses itens estão localizados. Se isso se tornar desconfortável, por favor, avise o tecnólogo e a pesquisadora.

Porque os participantes precisam estar imóveis no scanner, ocasionalmente, alguns relatam o desenvolvimento de pequenas dores no corpo, rigidez, dores de cabeça ou membros adormecendo. É importante que você tente ficar o mais confortável possível antes de iniciar a sessão de scanner, a fim de tentar minimizar esses efeitos.

Além disso, porque a parte superior do corpo é colocada dentro de um tubo estreito, alguns participantes podem experienciar claustrofobia. Devido ao espaço estreito, ruídos altos, ou por causa de tentar manter-se parado, alguns relatam que a respiração se torna mais curta. Nós encorajamos todos os participantes a relaxar e respirar normalmente (enquanto tenta manter a cabeça o mais imóvel possível). Se você sentir qualquer tipo de desconforto durante a sessão, por favor, avise o tecnólogo e a pesquisadora.

8. Alguém estará presente perto de mim durante o fMRI?

A sala do fMRI está localizada ao lado da sala de controle. Os pesquisadores normalmente ficam sentados na sala de controle durante a sessão, mas eles observam tudo que está acontecendo através de uma janela que liga as duas salas. Como a parte superior do seu corpo vai estar dentro do tubo de fMRI, os pesquisadores apenas podem ver a parte inferior do seu corpo. Há também um mini-câmera focada em seus olhos para que os pesquisadores possam assegurar que você está acordado durante a sessão. Haverá uma pesquisadora bilíngue (falante de português e inglês) com você em todas as sessões.

9. Posso falar com os pesquisadores durante o fMRI?

Enquanto você estiver no scanner e os pesquisadores estiverem na sala de controle, a equipe usará um interfone em intervalos regulares entre as tarefas para perguntar como você está, e para avisar sobre o que está por vir. Nessas ocasiões, você deve informá-los sobre quaisquer questões ou preocupações que você tenha, sejam questões relacionadas ao seu conforto, como você consegue ver as frases na tela, ou qualquer outra coisa. Se você tem alguma uma preocupação durante a sessão (desconforto ou qualquer problema com os estímulos experimentais sendo apresentados), você deve apertar a bola que será colocada sobre sua barriga enquanto você estiver no tubo de fMRI. O scanner é barulhento quando está em operação, mas apertando a bola, um alarme soará na sala de controle. Imediatamente, os pesquisadores vão falar com você pelo interfone, ou entrar na sala de scanner para falar com você diretamente. A equipe não será capaz de ouvi-lo falar enquanto o scanner estiver funcionando, e é por isso que você precisa apertar a bola para chamar a atenção dos pesquisadores e para que eles possam desligar o ruído do scanner.

10. O que eu devo fazer se notar um aparente problema com os estímulos durante o exame?

Se a tela mostrando os estímulos parecer ficar escura por um longo tempo, então é possível que as configurações de tela precisem ser ajustadas. Você deve alertar o tecnólogo pressionando a bola colocada sob sua barriga.

11. Alguém pode ficar comigo na sala do fMRI durante a sessão?

Se isso faria você se sentir muito mais confortável, uma pessoa que tenha passado pela mesma triagem de segurança que você passou pode sentar-se na sala de fMRI com você. Por exemplo, um dos nossos pesquisadores pode fazer isso. Você não será capaz de ver essa pessoa, mas ele(a) pode descansar a mão sobre seu pé para torná-lo consciente de sua presença, se isso fizer você se sentir mais confortável.

12. Existem medicamentos, alimentos, líquidos ou outros itens que devo evitar antes do meu dia de fMRI?

Evite cafeína no dia da sua sessão, pois ela pode fazer você ficar mais propenso a se mover, e também pode afetar a forma como seu cérebro funciona. Você também vai precisar evitar certos tipos de medicamentos que podem fazer você se sentir estimulado ou sonolento. Por favor, consulte-nos sobre os medicamentos antes da sua sessão. Além disso, evite café e outros diuréticos, pois podem exigir que você urine mais frequentemente, já que você não poderá usar o banheiro durante a sessão de fMRI (60 minutos).

13. Que conselhos eu devo seguir para ter uma sessão de fMRI bem sucedida?

Certifique-se de dormir o necessário na noite anterior à sua sessão de fMRI, pois assim você vai estar alerta e conseguirá prestar a atenção necessária durante as tarefas. Você deve evitar tudo que deixe você muito estimulado ou muito sonolento, como a cafeína e alguns medicamentos (pergunte-nos sobre detalhes). Você deve aproveitar a oportunidade para ir ao banheiro logo antes da sessão. Além disso, você pode pedir um pequeno copo de água para ter certeza de que você não vai sentir sede durante a sessão. Finalmente, você deve, durante a sessão, se concentrar apenas em realizar as tarefas conforme as instruções, e manter seu corpo (especialmente sua cabeça) o mais imóvel possível. Tente o seu melhor para manter o foco sobre as atividades durante todo o tempo em que você estiver no scanner.

14. E se eu precisar tossir, espirrar ou bocejar enquanto estiver no scanner?

Tente não tossir, espirrar ou bocejar, se você puder evitar. No entanto, se você realmente precisa e sabe que vai ter uma duração limitada, espere até uma pausa entre as tarefas (por exemplo, quando o pesquisador falar com você pelo interfone). Mas lembre-se de manter sua cabeça o mais imóvel possível. Se você achar que você realmente terá um acesso de tosse, espirros ou bocejos (o que implica muito movimento com sua cabeça), basta apertar a bola para alertar os pesquisadores da sua necessidade.

15. Devo participar da sessão de fMRI se eu tiver um resfriado ou alergias com congestão na cabeça ou no peito?

É melhor reagendar sua sessão se você tem congestão na cabeça ou no peito, ou se você está se sentindo mal de alguma forma. Assim que você perceber que você não pode participar, entre em contato conosco para nos avisar. Se você estiver sentindo um pouco mais ou menos (bem o suficiente para querer participar, mas ainda um pouco preocupado), por favor nos contate para podermos aconselhar você. Não tome medicamentos de gripe/resfriado no dia da sua sessão.

16. Por que eu tenho que ficar totalmente imóvel no scanner? Existe uma questão de segurança envolvida?

Você estará seguro no scanner, desde que você não tenha metal no seu corpo ou com você. No entanto, se você é incapaz de ficar totalmente imóvel no scanner, não poderemos alinhar corretamente as imagens de seu cérebro. Dessa forma, não podemos usar os dados de um participante que se mexeu durante a sessão de fMRI. É por esta razão que nós damos a você a oportunidade de participar de uma sessão de treino no simulador. Nesse treino, colocaremos um arco na sua cabeça para podermos determinar se você conseguirá ficar totalmente imóvel no scanner e produzir bons dados para os pesquisadores.

17. Quais são os critérios de exclusão do estudo?

Existem algumas restrições para os participantes de uma pesquisa fMRI. Porque a máquina de ressonância magnética é um ímã grande, as pessoas que têm metal em seus corpos não podem participar. Por metal perigoso entende-se: marca-passo, clipe de aneurisma, implante coclear, DIU, fragmentos de metal, body piercing não-removível, neuroestimulador, ou qualquer outro metal. Obturações dentárias são permitidas. Além disso, mulheres grávidas, pessoas que pesem mais de 136 kg, ou que sejam claustrofóbicas não devem participar pois podem experienciar desconforto. Neste estudo em particular, estamos interessados em investigar falantes nativos de português (com idade entre 18 e 35 anos) que são predominantemente destros.

18. Que tipo de roupa pode ser usada no scanner de fMRI?

Roupas confortáveis, folgadas e "quentinhas" devem ser usadas. Por exemplo, calça de moletom e uma camiseta são ideais porque eles não têm fechos de metal, botões de metal, ou outros acessórios. A sala com o scanner pode ser fria, devido ao ar condicionado sempre ligado, por isso temos um cobertor para oferecer. Metal na roupa deve ser evitado (a menos que seja uma pequena quantidade, como uma calça jeans). Por favor, não use cintos de metal, sutiãs com metal, roupas com fios metálicos ou botões metálicos ou fechos de metal em sua camisa. Se você usar calça jeans com botões de metal, zíper, ou rebites, não tem problema, pois ficam na parte inferior do seu corpo.

19. Pode usar jóias, acessórios ou outros itens no scanner?

Não podem ser usados grampos de cabelo de metal, jóias, relógios, anéis, brincos, etc. Caso você esteja usando, vamos pedir para você removê-los antes de entrar na sala do fMRI. Além disso, não entre na sala do fMRI com troco em moedas, chaves, telefones celulares ou outros objetos metálicos. Em especial, cartões de crédito e qualquer outro tipo de cartão que tenha uma tarja magnética não devem ser trazidos para a sala do fMRI porque eles serão apagados pelo ímã do scanner.

20. Pode usar maquiagem no dia da sessão de fMRI?

Raramente, certos tipos de maquiagem para os olhos (como delineadores) contêm partículas metálicas minúsculas que podem impedir a captura de imagens claras, ou que podem tornar-se desconfortavelmente quentes durante a sessão de fMRI. Se isso puder acontecer, será solicitado que você remova a maquiagem. Você deve evitar qualquer maquiagem que brilha ou que você sabe que tenha conteúdo metálico. Além disso, você deve considerar vir sem maquiagem para evitar de ter de removê-la.

21. Posso participar de um estudo com fMRI se estou grávida ou posso estar grávida?

Se você é uma mulher em idade fértil e você suspeitar que pode estar grávida, um teste de gravidez gratuito pode ser administrado antes que você ter permissão para participar. Se o teste der positivo, você não será poderá participar do estudo.

22. Óculos ou lentes de contato são permitidos no scanner de fMRI?

Você pode usar suas lentes de contatos no scanner. Se você usa óculos, forneceremos um par de óculos de plástico que aproximadamente correspondem à sua necessidade. Temos de -1 a -6 (para pessoas míopes) e de 1 a 5 (para pessoas hipermetropes).

23. Aparelhos ortodônticos permanentes ou retentores são permitidos no scanner?

Se você tiver aparelhos permanentes ou retentores, por favor nos avise para que possamos verificar se você pode participar do estudo. Não há nenhum risco para você, mas, dependendo do posicionamento e extensão do metal, ele pode causar artefatos em nossas imagens que tornariam essas imagens inutilizáveis para nós. Geralmente, os retentores permanentes podem ser usados, desde que sejam pequenos, e contanto que o metal esteja localizado na frente dos dentes (não sobre os dentes posteriores). Por favor, descobrir se o metal em seu aparelho ortodôntico é totalmente não-ferromagnético pode nos ajudar a determinar sua elegibilidade.

24. Que tipos de protetores de ouvido estarão disponíveis?

Tampões de ouvido industriais e fones de ouvido com atenuação de ruído estão disponíveis para ser usados como proteção auditiva. Se a sua audição é particularmente sensível, você pode solicitar que os dois tipos de proteção sejam usados simultaneamente.

25. Quanto tempo vai durar a minha sessão de fMRI?

Você participará de uma sessão de fMRI de aproximadamente 60 minutos.

26. O que eu tenho que fazer neste estudo? O que vai acontecer no dia d a minha sessão de fMRI?

Assim que você comunicar ao pesquisador sua decisão de participar, ela vai ligar para você ou escrever um e-mail para organizar a data do encontro para a coleta de dados, bem como do local de encontro. No dia e horário marcados, a pesquisadora lerá com você o formulário de consentimento para participação em pesquisa, você responderá a um questionário sobre lateralidade (atestar se você é destro, ambidestro ou canhoto) e um questionário sobre você. A pesquisadora vai explicar em detalhes a tarefa que você irá executar dentro do scanner de fMRI: pensar sobre o significado das palavras e frases conforme eles aparecem na tela. Você vai praticar a tarefa e, em seguida, você será levado para o simulador, de modo que você possa ter a oportunidade de sentir como a sessão no scanner real será. Neste momento, você deve fazer todas as perguntas que você possa ter sobre o procedimento. Você vai para a sala do scanner real e você ficará lá cerca de uma hora pensando sobre o significado das palavras e frases que serão apresentadas a você em português. Ao terminar a sessão no fMRI, a pesquisadora levará você para uma sala na qual você vai executar uma tarefa de reconhecimento, o que implica o reconhecimento das sentenças que você viu e não viu dentro do scanner, preencher um questionário sobre como você se sentiu no fMRI, além de realizar um teste de memória de trabalho em português, responder a um questionário rápido sobre ele e preencher um questionário sobre sua experiência linguística. Esta sessão vai durar cerca de 3 horas.

27. O que eu devo fazer se eu quiser sair durante a prática ou a sessão de fMRI?

Não há problema se você precisar fazer uma pausa ou precisar sair mais cedo. Alerte os pesquisadores imediatamente. Se você estiver no scanner, use a bola para chamar a atenção dos pesquisadores.

Se você tiver alguma dúvida (qualquer dúvida), não deixe de perguntar para a pesquisadora, seja pessoalmente ou por e-mail.

APPENDIX D

D1: Consent Form for the "English" scanning day - bilinguals

Carnegie Mellon University

Consent Form for Participation in Research Involving fMRI

Study Title: Neural Representations of Concept Meanings in Context

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Purpose of this Study
The purpose of this research study is to use functional magnetic resonance imaging (fMRI) to study language processing and thinking in normal adults. With fMRI, we obtain measures that indicate the blood flow in the brain. The techniques generate images of the magnetic resonance (MR) signals that result from the performance of tasks like reading a word to classify it (for example, deciding if the word is a noun or verb), or reading a sentence to decide if it is true or false.

Procedures
This study consists of three session visits to Carnegie Mellon University. Day 1 and Day 2 will have an fMRI scan. Prior to your fMRI scan, you will participate in a practice session. This practice session is to introduce you to the tasks you will see in the scanner and you will complete paper and pencil or onscreen tests involving language tasks. On Day 1, you will be screened for any exclusionary criteria that might prevent you from participating in an fMRI experiment. The screening requires you to answer a set of questions that will allow us to assess whether or not you meet the necessary criteria for participation. These questions and criteria are described later in this document.

Prior to the fMRI task, you will undergo a mock, or practice fMRI scan, particularly if you haven't been in an fMRI study previously. The mock MRI is a very realistic replica of the real scanner. The purpose of the mock scanner is to introduce you to the environment experienced in the scanner. The scanner simulation will take approximately 10-20 minutes. It includes training for minimizing head motion, hearing the sounds that the scanner makes, and practicing some of the tasks you will later see in the actual scanner. The simulation involves lying on a bed that slides into the mock MRI. You will look into a mirror fitted to a helmet / headcoil to see the tasks and respond using mouse buttons. The total amount of time for the practice session is 0.5-1 hour.

The actual MRI scanner is very similar to the mock MRI except that the actual MRI is a large magnet that will be collecting images of your brain as you complete the tasks. You will need to be screened

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again by the MRI technologist before participating in the fMRI, to insure that you are eligible to be scanned. After the screening, you will enter the MRI scanner where you will participate in the tasks that you have practiced. You will always be able to talk with the technologist during the study. The time in the actual MRI scanner will be from 1 to 2 hours. After your scan, you will be given an exit interview in which you will be asked questions about your experience during the study. This interview takes approximately 0.5 hour. All of the above procedures will take place at the Psychology Department and the Scientific Imaging and Brain Research Center at Carnegie Mellon University. The total amount of time for the fMRI scan and debriefing is 2.5 hours maximum for each Day 1 and Day 2.

At the conclusion of the sessions on Day 1 and 2, you will be asked about the scan and task. These questions will be audio recorded. The tapes will be transcribed and then erased. None of your personal information will be associated with these recordings.

On Day 3, you will complete paper and pencil tasks and/or onscreen tests involving language. The total amount of time for Day 3 will be 2.5 hours maximum.

Some of you who have successfully completed the fMRI study will be asked if you are willing to return for additional fMRI sessions. There could be up to 8-13 additional fMRI study sessions per year.

Also, those participants who do go on to participate in several additional studies of the same type may be asked to complete up to fifteen hours of an online web-based questionnaire from a location of your choice (such as your apartment) over a period of up to fifteen days. Questions will entail selecting, ranking, or scoring words and sentences as more or less related to one another.

Participant Requirements
People invited into this study have to be either males or females between 18 – 35 years of age in good health, who are bilingual in English and Portuguese or monolingual in Portuguese. In addition, you cannot participate if you have ever had a major head injury, have a history of nervous system diseases or movement disorders, have a general cognitive disorder, have a language-specific disorder or if you have a current diagnosis of, or are taking medication for, a psychiatric disorder. Some studies require that you be right-handed. These criteria are necessary to ensure a uniform subject population in terms of brain activations.
You may not participate in this study if:

- You know or have any suspicion that you may have a metallic object in your body. This includes things such as a cardiac pacemaker, cochlear implant, metal IUD (hormonal IUD's made of plastic are fine), neurostimulator, aneurysm clips, non-removable body piercing, history of shrapnel or metal fragments in the eye.

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- You are pregnant. If there is a possibility that you are pregnant you will be given a pregnancy test at no cost. If you are pregnant you will not be able to participate in the study. The risks of MRI to the fetus are felt to be very small, but are nevertheless also not known.
- You have a history of claustrophobia.
- You have permanent metal braces or a molar retainer.
- You weigh more than 300 pounds.

Risks

There is a potential risk of the powerful magnetic field of the magnet attracting ferromagnetic / metallic objects towards the magnet. For this reason you will be screened for metallic objects in your possession or in your body before entering the room with the magnet. All metallic items will be collected and placed in a locker outside the room. You must tell the technologist if you suspect you have any metal in your body.

General scanning risks include strain/fatigue, anxiety, discomfort or claustrophobia associated with remaining still. These are usually greatly alleviated by the practice session where you will have the opportunity to acclimate to the scanner environment in the mock-scanner. Additionally, you will be able to speak with the technician/experimenter over an intercom system throughout the scan. A Portuguese speaking experimenter will be present for all scans with Portuguese monolinguals.

To alleviate the possibility of discomfort associated with the sound of the MRI scanner, you will wear earplugs and/or sound padding over your ears.

The possibility exists that the MRI scans will indicate something unusual or different about your brain that has nothing to do with this study. Should this happen, the technologist will ask a qualified radiologist to review the scans. There will be no charge to you for this review. We will contact you with the radiologist's findings if the radiologist advises it within three weeks of the scan.

There is also a remote possibility of a breach of confidentiality as a possible risk. We have never had any previous occurrences with this issue, and all consent forms are securely locked away to further ensure that no breaches of confidentiality will occur.

Benefits

There may be no personal benefit from your participation in the study but the knowledge received may be of value to humanity.
This research is sponsored by the U.S. government and the DoD may access or inspect the records for auditing purposes.

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Incidental Findings
There is a remote possibility that the MRI will indicate something unusual or different about your brain that has nothing to do with this study. The MRI is being done to answer research questions, not diagnose brain disorders. In the unlikely event that a member of the research team notices what looks like possibly significant abnormalities in the scans of your brain, the technologist will ask a qualified radiologist to review the scans. There will be no charge to you for this review. We will contact you with the radiologist's findings if the radiologist advises us to do so. You will be responsible for following up with your physician if anything is identified.

Compensation & Costs
You will receive $30 for your participation in the practice sessions on Days 1 and 2 and $45 for your participation in the fMRI scans on Days 1 and 2. You may be awarded additional bonus payments (up to $15) several weeks after the scan, as a reward for refraining from moving your head substantially throughout the entire scan. As long as you attempt the practice session, you will be paid $30. As long as you attempt the fMRI scan, you will be paid $75 for each Day 1 and Day 2. If you are unwilling to attempt the practice session or fMRI scan you will not receive payment. On Day 3, you will be compensated $10/hour for the behavioral tasks.

If you are participating in a pilot experiment, you will only participate in behavioral portion of the practice session and will not participate in either the mock or experimental MRI scan. You will not need to be screened for exclusionary MRI criteria. The total amount of time for your participation in a pilot experiment is between .5 and 1 hour. You will receive $5-$10 for your participation in a pilot experiment, corresponding to $5 per half hour of your time.

If you are asked to complete the online behavioral studies, you will be compensated $10/hour for completed time-on-task. Time-on-task refers to the amount of time spent engaging with the task (reading and responding to questions), which is tracked by the online application. You are not compensated for time spent logged into the online application but not engaged with the task. You will also receive a $100 bonus for completing all requested work by the completion date. You may stop participation at any time, and will receive a pro-rated amount of compensation based on the amount of time-on-task completed.

If you are asked to return for additional fMRI sessions, you will receive a $200 bonus for completing all requested MRI sessions by the completion date that will be agreed upon with you.

There will be no cost to you if you participate in this study.

Medical Treatment Costs
Carnegie Mellon University is not offering financial compensation, payment for the costs of medical treatment, or emergency care should you be injured as a result of participating in this study.

Carnegie Mellon University

Consent Form for Participation in Research Involving fMRI

Confidentiality
By participating in the study, you understand and agree that Carnegie Mellon may be required to disclose your consent form, data and other personally identifiable information as required by law, regulation, subpoena, or court order. Otherwise, your confidentiality will be maintained in the following manner:

Your identity on the research data will be indicated by a number rather than by your name, and the information linking the number with your identity will be kept separate from the research data. Only the researchers listed on the first page of this form and their staff will have access to your research records. All research data are kept on a secured computer system.

Your consent form will be stored in a locked location on Carnegie Mellon property and will not be disclosed to third parties. By participating, you understand and agree that the data and information gathered during this study may be used by Carnegie Mellon and published and/or disclosed by Carnegie Mellon to others outside of Carnegie Mellon. However, your name, address, contact information, and other direct personal identifiers in your consent form will not be mentioned in any such publication or dissemination of the research data and/or results by Carnegie Mellon. If the researchers learn that you or someone with whom you are involved is in serious danger or harm, they will need to inform the appropriate agencies as required by Pennsylvania law.

Rights
Your participation is voluntary. You are free to stop your participation at any point. Also, you can choose not to participate in this study. Refusal to participate or withdrawal of your consent or discontinued participation in the study will not result in any penalty or loss of benefits or rights to which you might otherwise be entitled. The Principal Investigator may at his/her discretion remove you from the study for any of a number of reasons. In such an event, you will not suffer any penalty or loss of benefits or rights which you might otherwise be entitled.

Right to Ask Questions & Contact Information
If you have any questions about this study, you should feel free to ask them now. If you have questions later, desire additional information, or wish to withdraw your participation, please contact the Principal Investigator by mail, phone, or e-mail in accordance with the contact information listed on the first page of this consent.

If you have questions pertaining to your rights as a research participant; or to report objections to this study, you should contact the Research Regulatory Compliance Office at Carnegie Mellon University. Email: irb-review@andrew.cmu.edu Phone: 412-268-1901 or 412-268-5460.

Carnegie Mellon University

Consent Form for Participation in Research Involving fMRI

Voluntary Consent

By signing below, you agree that the above information has been explained to you and all your current questions have been answered. You understand that you may ask questions about any aspect of this research study during the course of the study and in the future. By signing this form, you agree to participate in this research study.

PARTICIPANT SIGNATURE DATE

I certify that I have explained the nature and purpose of this research study to the above individual and I have discussed the potential benefits and possible risks of participation in the study. Any questions the individual has about this study have been answered and any future questions will be answered as they arise.

SIGNATURE OF PERSON OBTAINING CONSENT DATE

D2: Consent Form for the "Portuguese" scanning day – bilinguals

Universidade Carnegie Mellon

Termo de Consentimento Livre e Esclarecido para Participação em Pesquisa Envolvendo fMRI

Título do Estudo: Representações Neurais do Significado de Conceitos em Contexto

Investigator Principal: Marcel Adam Just, Ph.D.
Departmento de Psicologia, Universidade Carnegie Mellon
Baker Hall, 327H, Pittsburgh, PA 15213
Telefone: 412-268-2791, Email: just@cmu.edu

Orientador da faculdade:

Outro(s) investigadore(s): Tom Mitchell, Ph.D., Departamento de Aprendizagem de Máquina, CMU, 412-268-2611

Objetivo deste Estudo
O objetivo deste estudo é utilizar ressonância magnética funcional (do inglês, fMRI) para estudar o processamento da linguagem e do pensamento em adultos normais. Com fMRI, obtemos medidas que indicam o fluxo de sangue no cérebro. As técnicas geram imagens a partir do sinal de ressonância magnética (MR) que resultam da realização de tarefas como a leitura de uma palavra para classificá-la (por exemplo, decidir se a palavra é um substantivo ou verbo), ou a leitura de uma sentença para decidir se ela é verdadeira ou falsa.

Procedimentos
Este estudo envolve três sessões na Universidade Carnegie Mellon. Nos dias 1 e 2 teremos sessão de fMRI. Antes da sua sessão de fMRI, você vai participar de uma sessão de treino. Esta sessão de treino serve para apresentar as tarefas que você vai desempenhar no scanner e também para completar testes em papel e lápis ou testes na tela do computador que envolvem tarefas com linguagem. No dia 1, será feito uma triagem: você responderá algumas perguntas acerca de critérios de exclusão que podem impedi-lo de participar de um experimento com fMRI. A triagem exige que você responda um conjunto de questões que nos permitirá avaliar se você atende ou não aos critérios necessários para a participação. Estas perguntas e critérios estão descritos mais adiante neste documento.

Antes da tarefa com fMRI, você passará por um simulador de fMRI, especialmente se você não participou de um estudo com fMRI anteriormente. O simulador é uma réplica muito realista do scanner real. O objetivo é introduzi-lo ao ambiente que você experienciará no scanner. A simulação demorará em torno de 10-20 minutos. Esta parte inclui treinamento para minimizar o movimento da cabeça, você ouvirá os sons que o scanner faz, e praticará algumas das tarefas que você vai ver mais tarde no scanner real. A simulação envolve deitar em uma cama que desliza para dentro do simulador de ressonância magnética. Você vai olhar para um espelho montado em um suporte acima da sua cabeça para ver as tarefas e vai responder usando os botões do *mouse*. A quantidade total de tempo para a sessão de treino é de 0,5-1 hora.

O scanner de ressonância magnética real é muito parecido com o simulador, exceto pelo fato de que o MRI real é um grande ímã que estará coletando imagens de seu cérebro conforme você completa as tarefas. O técnico de MRI perguntará a você novamente as perguntas da triagem para assegurar que você realmente pode participar. Após essa nova triagem, você entrará no scanner e participará do estudo, executando as tarefas que você treinou no simulador. Você poderá falar com o técnico durante o estudo sempre que precisar. O tempo no scanner real levará de 1 a 2 horas. Após a sessão, você será entrevistado em relação à sua experiência durante o estudo. Esta entrevista demora cerca de meia hora. Todos os procedimentos acima serão realizada no Departamento de Psicologia e no Centro de Imageamento Cerebral da Universidade Carnegie Mellon. A quantia total de tempo para a sessão de fMRI e a entrevista é de cerca de 2 horas e meia para os dias 1 e 2.

Ao término das sessões nos dias 1 e 2, algumas perguntas serão feitas a você sobre a sessão de fMRI e as tarefas que você acabou de desempenhar. Estas perguntas serão gravadas em áudio. As fitas serão transcritas e depois, apagadas. Nenhum dos seus dados pessoais serão associados a essas gravações.

No dia 3, você vai completar testes em papel e lápis ou testes na tela do computador que envolvem tarefas com linguagem. A quantia total de tempo para o dia 3 será de, no máximo, 2h e meia.

Alguns de vocês que tenham concluído com êxito o estudo de fMRI poderão ser convidados a retornar para sessões adicionais de fMRI. Poderíamos convidá-lo a participar de até 8-13 sessões adicionais de estudo com fMRI por ano.

Além disso, os participantes que passam a participar de vários estudos adicionais do mesmo tipo podem ser solicitados a completar até 15 horas de um questionário *online* em um local de sua escolha (como sua casa, apartamento) durante um período de até quinze dias. As perguntas envolvem selecionar, classificar ou marcar palavras e frases como mais ou menos relacionadas entre si.

Requisitos dos Participantes

As pessoas convidadas para este estudo são homens e mulheres entre 18-35 anos de idade em bom estado de saúde, que são falantes bilíngues de inglês e português, ou falantes monolíngues de português. Mesmo preenchendo estes requisitos, você não poderá participar se você já teve um grande ferimento na cabeça, se tiver um histórico de doenças do sistema nervoso ou distúrbios de movimento, se tiver algum distúrbio cognitivo geral, se tiver um distúrbio específico de linguagem ou se tiver um diagnóstico atual de transtorno psiquiátrico ou se estiver tomando medicação para algum transtorno psiquiátrico. Alguns estudos exigem que você seja destro. Estes critérios são necessários para assegurar uma população de participantes uniforme em termos de ativações cerebrais.

Você não poderá participar deste estudo se:

- Você sabe ou tem alguma suspeita de que você tem ou pode ter um objeto metálico em seu corpo. Isto inclui coisas como um marca-passo, implante coclear, DIU (dispositivo intra-uterino) feito de metal (os feitos de plástico estão OK), neuroestimulador, clips de aneurisma, *piercing* não-removível, ou alguma experiência com estilhaços ou fragmentos de metal nos olhos.
- Você está grávida. Se houver a possibilidade de você estar grávida, nós daremos um teste de gravidez para você, sem custo. Se você estiver grávida, você não poderá participar do estudo. Os riscos da ressonância magnética para o feto são muito pequenos, mas seu efeito não é conhecido por completo.
- Você tem um histórico de claustrofobia.
- Você tem aparelho dental metálico ou um retentor molar.
- Você pesa mais de 300 libras/135 kg.

Riscos

Há um risco em potencial de o poderoso campo magnético do ímã atrair objetos ferromagnéticos/metálicos para o ímã. Por esta razão, faremos uma triagem e você responderá diversas perguntas sobre objetos metálicos em sua posse ou em seu corpo antes de entrar na sala com o ímã. Todos os itens metálicos serão coletados e guardados em um armário fora do sala de fMRI. Você deve dizer ao técnico se você suspeitar que tem qualquer metal em seu corpo.

Riscos gerais da sessão de fMRI incluem tensão/fadiga, ansiedade, desconforto ou claustrofobia associada com a necessidade de ficar imóvel. Estes riscos são reduzidos na sessão de treino, onde você terá a oportunidade de se adaptar ao ambiente do scanner no simulador. Além disso, você será capaz de falar com o técnico/pesquisador através de um intercomunicador durante a sessão inteira. Um pesquisador falante nativo de português estará presente em todas as sessões com os participantes monolíngues.

Para aliviar a possibilidade de desconforto associado com o som do scanner de ressonância magnética, você vai usar protetores de ouvido e/ou preenchimento de espuma sobre suas orelhas.

Existe a possibilidade de que as sessões com fMRI identifiquem algo incomum ou diferente sobre o seu cérebro que não tem nada a ver com este estudo. Caso isto aconteça, o técnico vai pedir a um radiologista qualificado para analisar as imagens. Não haverá nenhum custo para você. Entraremos em contato sobre as conclusões do radiologista, se o radiologista achar necessário, em torno de três semanas após a sessão.

Termo de Consentimento Livre e Esclarecido para Participação em Pesquisa Envolvendo fMRI

Há também uma possibilidade remota de quebra de sigilo como um possível risco. Nós nunca tivemos quaisquer ocorrências anteriores com este problema. Todas as formas de consentimento estão devidamente guardadas em segurança para garantir que não haja quebra de confidencialidade.

Benefícios
Pode não haver benefício pessoal a partir da sua participação no estudo, mas o conhecimento recebido pode ser de grande valor para a humanidade.
Esta pesquisa é patrocinada pelo governo dos EUA e o Departamento de Defesa pode acessar ou inspecionar os registros para fins de auditoria.

Achados Incidentes
Existe uma possibilidade remota de que a ressonância magnética pode indicar algo incomum ou diferente sobre o seu cérebro que não tem nada a ver com este estudo. Os experimentos com fMRI estão sendo feitos para responder perguntas de pesquisa, não para diagnosticar distúrbios cerebrais. No caso improvável de um membro da equipe de pesquisa perceber algo que possa ser uma alteração significativa nas imagens do seu cérebro, o técnico pedirá a um radiologista qualificado para analisar as imagens. Não haverá nenhum custo para você. Entraremos em contato sobre as conclusões do radiologista se o radiologista nos aconselhar a fazê-lo. Você será responsável pelo acompanhamento com seu médico se algo for identificado.

Compensação & Custos
Você receberá U$30 pela sua participação nas sessões de treino nos dias 1 e 2 e U$45 pela sua participação no fMRI nos dias 1 e 2. Você pode receber bônus adicionais (de até U$15) várias semanas após a sessão, como uma recompensa por ter ficado completamente imóvel durante toda a sessão. Se você fizer apenas a sessão de prática, receberá U$30. Se você participar da sessão de fMRI, receberá $75 para cada dia, 1 e 2. Se você não está disposto a tentar a sessão de treino ou a sessão de fMRI, você não receberá o pagamento. No dia 3, você receberá U$10/hora para as tarefas comportamentais.

Se você está participando de um experimento piloto, você só vai participar da parte comportamental da sessão de treino e não vai participar da sessão de treino no simulador nem da sessão com fMRI. Você não vai precisar passar pela triagem acerca dos critérios de exclusão do experimento com fMRI. A quantia total de tempo para a sua participação em um experimento piloto é de meia hora a 1 hora. Você receberá U$5-$10 pela sua participação, correspondendo a U$5 por cada meia hora do seu tempo.

Se você for convidado para completar os estudos comportamentais *online*, você receberá U$10/hora para o tempo de tarefa concluída. Tempo de tarefa concluída se refere à quantidade de tempo que o participante gasta envolvido com a tarefa (ler e responder perguntas) e esse tempo é controlado pelo aplicativo *online*. Você não receberá pagamento pelo tempo que estiver conectado ao aplicativo *online* sem fazer a tarefa. Além dos U$10/hora, você receberá um bônus de U$100 por completar todo o trabalho solicitado até a data estabelecida. Você pode parar de participar a qualquer momento, e vai receber um montante proporcional de remuneração com base na quantidade de tempo de tarefa concluída.

Se você for convidado a retornar para sessões adicionais de fMRI, você receberá um bônus de U$200 por completar todas as sessões de fMRI até a data acordada com você.

Não haverá nenhum custo para você se você participar deste estudo.

Custos com Tratamento Médico
A Universidade Carnegie Mellon não está oferecendo compensação financeira, ou pagamento por custos de tratamento médico, ou por atendimento de emergência no caso de você se machucar ao participar deste estudo.

Confidencialidade
Ao participar do estudo, você entende e concorda que a Carnegie Mellon pode ser obrigada a revelar o seu consentimento, seus dados e outras informações pessoalmente identificáveis conforme exigido por lei, regulamento, intimação ou ordem judicial. Caso contrário, a sua confidencialidade será mantida da seguinte forma:

Sua identidade nos dados da pesquisa será indicada por um número em vez de pelo seu nome, e as informações de vinculação do número com a sua identidade serão mantidas separadas dos dados da pesquisa. Apenas os pesquisadores listados na primeira página deste formulário e seus funcionários terão acesso aos registros da pesquisa. Todos os dados da pesquisa são mantidos em um sistema de computador protegido.

O formulário de consentimento será armazenado em um local seguro e trancado em uma das propriedades da Carnegie Mellon e não será divulgado a terceiros. Ao participar, você entende e concorda que os dados e informações recolhidas durante este estudo poderão ser utilizados pela Carnegie Mellon e publicados e/ou divulgados pela Carnegie Mellon para outros fora da Carnegie Mellon. No entanto, o seu nome, endereço, informações de contato e outros identificadores pessoais diretos em seu formulário de consentimento não serão mencionados em qualquer publicação ou divulgação dos dados de pesquisa e/ou resultados pela Carnegie Mellon. Se os pesquisadores souberem que você ou alguém com quem você está envolvido está em grave perigo ou dano, eles terão de informar os órgãos competentes, conforme exigido por lei no estado da Pensilvânia.

Universidade Carnegie Mellon

Termo de Consentimento Livre e Esclarecido para Participação em Pesquisa Envolvendo fMRI

Direitos
Sua participação é voluntária. Você é livre para interromper sua participação a qualquer momento. Além disso, você pode optar por não participar deste estudo. A recusa em participar ou a retirada de seu consentimento ou a participação descontinuada no estudo não acarretará qualquer penalidade ou perda de benefícios ou direitos a que você teria direito. O pesquisador principal pode, em seu discernimento, removê-lo do estudo por uma série de razões. Nesse caso, você não vai sofrer qualquer penalidade ou perda de benefícios ou direitos que você poderia ter direito.

Direito de Fazer Perguntas & Informações de Contato
Se você tem alguma dúvida sobre este estudo, você deve sentir-se livre para perguntar agora. Se você tiver dúvidas mais tarde, desejar obter mais informações, ou desejar parar de participar deste estudo, entre em contato com o Investigador Principal por correio, telefone ou e-mail, de acordo com as informações de contato listado na primeira página deste consentimento.

Se você tem perguntas sobre seus direitos como participante de pesquisa; ou denunciar objeções a este estudo, você deve contatar o Escritório Regulador de Consentimento de Pesquisa (Regulatory Compliance Office Research) da Universidade Carnegie Mellon. E-mail: irb-review@andrew.cmu.edu Telefone: 412-268-1901 ou 412-268-5460.

Consentimento Voluntário

Ao assinar abaixo, você concorda que as informações acima foram explicadas a você e todas as suas perguntas atuais foram respondidas. Você entende que você pode fazer perguntas sobre qualquer aspecto deste estudo durante o curso do estudo e no futuro. Ao assinar este formulário, você concorda em participar desta pesquisa.

____________________________________ __________________
ASSINATURA DO PARTICIPANTE DATA

Eu declaro que eu expliquei a natureza e o objetivo deste estudo para o indivíduo acima e eu discuti com ele(a) os benefícios em potencial e os eventuais riscos da sua participação no estudo. Quaisquer dúvidas que o indivíduo tem sobre este estudo foram respondidas e todas as perguntas futuras serão respondidas conforme elas surgirem.

____________________________________ __________________
ASSINATURA DA PESSOA OBTENDO CONSENTIMENTO DATA

D3: Consent Form for monolinguals

Universidade Carnegie Mellon

Termo de Consentimento Livre e Esclarecido para Participação em Pesquisa Envolvendo fMRI

Título do Estudo: Representações Neurais do Significado de Conceitos em Contexto

Investigator Principal: Marcel Adam Just, Ph.D.
Departmento de Psicologia, Universidade Carnegie Mellon
Baker Hall, 327H, Pittsburgh, PA 15213
Telefone: 412-268-2791, Email: just@cmu.edu

Orientador da faculdade:

Outro(s) investigadore(s): Tom Mitchell, Ph.D., Departamento de Aprendizagem de Máquina, CMU, 412-268-2611

Objetivo deste Estudo
O objetivo deste estudo é utilizar ressonância magnética funcional (do inglês, fMRI) para estudar o processamento da linguagem e do pensamento em adultos normais. Com fMRI, obtemos medidas que indicam o fluxo de sangue no cérebro. As técnicas geram imagens a partir do sinal de ressonância magnética (MR) que resultam da realização de tarefas como a leitura de uma palavra para classificá-la (por exemplo, decidir se a palavra é um substantivo ou verbo), ou a leitura de uma sentença para decidir se ela é verdadeira ou falsa.

Procedimentos
Este estudo envolve três sessões na Universidade Carnegie Mellon. Nos dias 1 e 2 teremos sessão de fMRI. Antes da sua sessão de fMRI, você vai participar de uma sessão de treino. Esta sessão de treino serve para apresentar as tarefas que você vai desempenhar no scanner e também para completar testes em papel e lápis ou testes na tela do computador que envolvem tarefas com linguagem. No dia 1, será feito uma triagem: você responderá algumas perguntas acerca de critérios de exclusão que podem impedi-lo de participar de um experimento com fMRI. A triagem exige que você responda um conjunto de questões que nos permitirá avaliar se você atende ou não aos critérios necessários para a participação. Estas perguntas e critérios estão descritos mais adiante neste documento.

Antes da tarefa com fMRI, você passará por um simulador de fMRI, especialmente se você não participou de um estudo com fMRI anteriormente. O simulador é uma réplica muito realista do scanner real. O objetivo é introduzi-lo ao ambiente que você experienciará no scanner. A simulação demorará em torno de 10-20 minutos. Esta parte inclui treinamento para minimizar o movimento da cabeça, você ouvirá os sons que o scanner faz, e praticará algumas das tarefas que você vai ver mais tarde no scanner real. A simulação envolve deitar em uma cama que desliza para dentro do simulador de ressonância magnética. Você vai olhar para um espelho montado em um suporte acima da sua cabeça para ver as tarefas e vai responder usando os botões do *mouse*. A quantidade total de tempo para a sessão de treino é de 0,5-1 hora.

O scanner de ressonância magnética real é muito parecido com o simulador, exceto pelo fato de que o MRI real é um grande ímã que estará coletando imagens de seu cérebro conforme você completa as tarefas. O técnico de MRI perguntará a você novamente as perguntas da triagem para assegurar que você realmente pode participar. Após essa nova triagem, você entrará no scanner e participará do estudo, executando as tarefas que você treinou no simulador. Você poderá falar com o técnico durante o estudo sempre que precisar. O tempo no scanner real levará de 1 a 2 horas. Após a sessão, você será entrevistado em relação à sua experiência durante o estudo. Esta entrevista demora cerca de meia hora. Todos os procedimentos acima serão realizada no Departamento de Psicologia e no Centro de Imageamento Cerebral da Universidade Carnegie Mellon. A quantia total de tempo para a sessão de fMRI e a entrevista é de cerca de 2 horas e meia para os dias 1 e 2.

Ao término das sessões nos dias 1 e 2, algumas perguntas serão feitas a você sobre a sessão de fMRI e as tarefas que você acabou de desempenhar. Estas perguntas serão gravadas em áudio. As fitas serão transcritas e depois, apagadas. Nenhum dos seus dados pessoais serão associados a essas gravações.

No dia 3, você vai completar testes em papel e lápis ou testes na tela do computador que envolvem tarefas com linguagem. A quantia total de tempo para o dia 3 será de, no máximo, 2h e meia.

Alguns de vocês que tenham concluído com êxito o estudo de fMRI poderão ser convidados a retornar para sessões adicionais de fMRI. Poderíamos convidá-lo a participar de até 8-13 sessões adicionais de estudo com fMRI por ano.

Além disso, os participantes que passam a participar de vários estudos adicionais do mesmo tipo podem ser solicitados a completar até 15 horas de um questionário *online* em um local de sua escolha (como sua casa, apartamento) durante um período de até quinze dias. As perguntas envolvem selecionar, classificar ou marcar palavras e frases como mais ou menos relacionadas entre si.

Requisitos dos Participantes
As pessoas convidadas para este estudo são homens e mulheres entre 18-35 anos de idade em bom estado de saúde, que são falantes bilíngues de inglês e português, ou falantes monolíngues de português. Mesmo preenchendo estes requisitos, você não poderá participar se você já teve um grande ferimento na cabeça, se tiver um histórico de doenças do sistema nervoso ou distúrbios de movimento, se tiver algum distúrbio cognitivo geral, se tiver um distúrbio específico de linguagem ou se tiver um diagnóstico atual de transtorno psiquiátrico ou se estiver tomando medicação para algum

transtorno psiquiátrico. Alguns estudos exigem que você seja destro. Estes critérios são necessários para assegurar uma população de participantes uniforme em termos de ativações cerebrais.

Você não poderá participar deste estudo se:

- Você sabe ou tem alguma suspeita de que você tem ou pode ter um objeto metálico em seu corpo. Isto inclui coisas como um marca-passo, implante coclear, DIU (dispositivo intra-uterino) feito de metal (os feitos de plástico estão OK), neuroestimulador, clips de aneurisma, *piercing* não-removível, ou alguma experiência com estilhaços ou fragmentos de metal nos olhos.
- Você está grávida. Se houver a possibilidade de você estar grávida, nós daremos um teste de gravidez para você, sem custo. Se você estiver grávida, você não poderá participar do estudo. Os riscos da ressonância magnética para o feto são muito pequenos, mas seu efeito não é conhecido por completo.
- Você tem um histórico de claustrofobia.
- Você tem aparelho dental metálico ou um retentor molar.
- Você pesa mais de 300 libras/135 kg.

Riscos

Há um risco em potencial de o poderoso campo magnético do ímã atrair objetos ferromagnéticos/metálicos para o ímã. Por esta razão, faremos uma triagem e você responderá diversas perguntas sobre objetos metálicos em sua posse ou em seu corpo antes de entrar na sala com o ímã. Todos os itens metálicos serão coletados e guardados em um armário fora do sala de fMRI. Você deve dizer ao técnico se você suspeitar que tem qualquer metal em seu corpo.

Riscos gerais da sessão de fMRI incluem tensão/fadiga, ansiedade, desconforto ou claustrofobia associada com a necessidade de ficar imóvel. Estes riscos são reduzidos na sessão de treino, onde você terá a oportunidade de se adaptar ao ambiente do scanner no simulador. Além disso, você será capaz de falar com o técnico/pesquisador através de um intercomunicador durante a sessão inteira. Um pesquisador falante nativo de português estará presente em todas as sessões com os participantes monolíngues.

Para aliviar a possibilidade de desconforto associado com o som do scanner de ressonância magnética, você vai usar protetores de ouvido e/ou preenchimento de espuma sobre suas orelhas.

Existe a possibilidade de que as sessões com fMRI identifiquem algo incomum ou diferente sobre o seu cérebro que não tem nada a ver com este estudo. Caso isto aconteça, o técnico vai pedir a um radiologista qualificado para analisar as imagens. Não haverá nenhum custo para você. Entraremos em contato sobre as conclusões do radiologista, se o radiologista achar necessário, em torno de três semanas após a sessão.

Termo de Consentimento Livre e Esclarecido para Participação em Pesquisa Envolvendo fMRI

Há também uma possibilidade remota de quebra de sigilo como um possível risco. Nós nunca tivemos quaisquer ocorrências anteriores com este problema. Todas as formas de consentimento estão devidamente guardadas em segurança para garantir que não haja quebra de confidencialidade.

Benefícios
Pode não haver benefício pessoal a partir da sua participação no estudo, mas o conhecimento recebido pode ser de grande valor para a humanidade.
Esta pesquisa é patrocinada pelo governo dos EUA e o Departamento de Defesa pode acessar ou inspecionar os registros para fins de auditoria.

Achados Incidentes
Existe uma possibilidade remota de que a ressonância magnética pode indicar algo incomum ou diferente sobre o seu cérebro que não tem nada a ver com este estudo. Os experimentos com fMRI estão sendo feitos para responder perguntas de pesquisa, não para diagnosticar distúrbios cerebrais. No caso improvável de um membro da equipe de pesquisa perceber algo que possa ser uma alteração significativa nas imagens do seu cérebro, o técnico pedirá a um radiologista qualificado para analisar as imagens. Não haverá nenhum custo para você. Entraremos em contato sobre as conclusões do radiologista se o radiologista nos aconselhar a fazê-lo. Você será responsável pelo acompanhamento com seu médico se algo for identificado.

Compensação & Custos
Você receberá U$30 pela sua participação nas sessões de treino nos dias 1 e 2 e U$45 pela sua participação no fMRI nos dias 1 e 2. Você pode receber bônus adicionais (de até U$15) várias semanas após a sessão, como uma recompensa por ter ficado completamente imóvel durante toda a sessão. Se você fizer apenas a sessão de prática, receberá U$30. Se você participar da sessão de fMRI, receberá $75 para cada dia, 1 e 2. Se você não está disposto a tentar a sessão de treino ou a sessão de fMRI, você não receberá o pagamento. No dia 3, você receberá U$10/hora para as tarefas comportamentais.

Se você está participando de um experimento piloto, você só vai participar da parte comportamental da sessão de treino e não vai participar da sessão de treino no simulador nem da sessão com fMRI. Você não vai precisar passar pela triagem acerca dos critérios de exclusão do experimento com fMRI. A quantia total de tempo para a sua participação em um experimento piloto é de meia hora a 1 hora. Você receberá U$5-$10 pela sua participação, correspondendo a U$5 por cada meia hora do seu tempo.

Se você for convidado para completar os estudos comportamentais *online*, você receberá U$10/hora para o tempo de tarefa concluída. Tempo de tarefa concluída se refere à quantidade de tempo que o participante gasta envolvido com a tarefa (ler e responder perguntas) e esse tempo é controlado pelo aplicativo *online*. Você não receberá pagamento pelo tempo que estiver conectado ao aplicativo *online* sem fazer a tarefa. Além dos U$10/hora, você receberá um bônus de U$100 por completar todo o trabalho solicitado até a data estabelecida. Você pode parar de participar a qualquer momento, e vai receber um montante proporcional de remuneração com base na quantidade de tempo de tarefa concluída.

Se você for convidado a retornar para sessões adicionais de fMRI, você receberá um bônus de U$200 por completar todas as sessões de fMRI até a data acordada com você.

Não haverá nenhum custo para você se você participar deste estudo.

Custos com Tratamento Médico
A Universidade Carnegie Mellon não está oferecendo compensação financeira, ou pagamento por custos de tratamento médico, ou por atendimento de emergência no caso de você se machucar ao participar deste estudo.

Confidencialidade
Ao participar do estudo, você entende e concorda que a Carnegie Mellon pode ser obrigada a revelar o seu consentimento, seus dados e outras informações pessoalmente identificáveis conforme exigido por lei, regulamento, intimação ou ordem judicial. Caso contrário, a sua confidencialidade será mantida da seguinte forma:

Sua identidade nos dados da pesquisa será indicada por um número em vez de pelo seu nome, e as informações de vinculação do número com a sua identidade serão mantidas separadas dos dados da pesquisa. Apenas os pesquisadores listados na primeira página deste formulário e seus funcionários terão acesso aos registros da pesquisa. Todos os dados da pesquisa são mantidos em um sistema de computador protegido.

O formulário de consentimento será armazenado em um local seguro e trancado em uma das propriedades da Carnegie Mellon e não será divulgado a terceiros. Ao participar, você entende e concorda que os dados e informações recolhidas durante este estudo poderão ser utilizados pela Carnegie Mellon e publicados e/ou divulgados pela Carnegie Mellon para outros fora da Carnegie Mellon. No entanto, o seu nome, endereço, informações de contato e outros identificadores pessoais diretos em seu formulário de consentimento não serão mencionados em qualquer publicação ou divulgação dos dados de pesquisa e/ou resultados pela Carnegie Mellon. Se os pesquisadores souberem que você ou alguém com quem você está envolvido está em grave perigo ou dano, eles terão de informar os órgãos competentes, conforme exigido por lei no estado da Pensilvânia.

Universidade Carnegie Mellon

Termo de Consentimento Livre e Esclarecido para Participação em Pesquisa Envolvendo fMRI

Direitos
Sua participação é voluntária. Você é livre para interromper sua participação a qualquer momento. Além disso, você pode optar por não participar deste estudo. A recusa em participar ou a retirada de seu consentimento ou a participação descontinuada no estudo não acarretará qualquer penalidade ou perda de benefícios ou direitos a que você teria direito. O pesquisador principal pode, em seu discernimento, removê-lo do estudo por uma série de razões. Nesse caso, você não vai sofrer qualquer penalidade ou perda de benefícios ou direitos que você poderia ter direito.

Direito de Fazer Perguntas & Informações de Contato
Se você tem alguma dúvida sobre este estudo, você deve sentir-se livre para perguntar agora. Se você tiver dúvidas mais tarde, desejar obter mais informações, ou desejar parar de participar deste estudo, entre em contato com o Investigador Principal por correio, telefone ou e-mail, de acordo com as informações de contato listado na primeira página deste consentimento.

Se você tem perguntas sobre seus direitos como participante de pesquisa; ou denunciar objeções a este estudo, você deve contatar o Escritório Regulador de Consentimento de Pesquisa (Regulatory Compliance Office Research) da Universidade Carnegie Mellon. E-mail: irb-review@andrew.cmu.edu Telefone: 412-268-1901 ou 412-268-5460.

Consentimento Voluntário

Ao assinar abaixo, você concorda que as informações acima foram explicadas a você e todas as suas perguntas atuais foram respondidas. Você entende que você pode fazer perguntas sobre qualquer aspecto deste estudo durante o curso do estudo e no futuro. Ao assinar este formulário, você concorda em participar desta pesquisa.

______________________________ ________________

ASSINATURA DO PARTICIPANTE DATA

Eu declaro que eu expliquei a natureza e o objetivo deste estudo para o indivíduo acima e eu discuti com ele(a) os benefícios em potencial e os eventuais riscos da sua participação no estudo. Quaisquer dúvidas que o indivíduo tem sobre este estudo foram respondidas e todas as perguntas futuras serão respondidas conforme elas surgirem.

______________________________ ________________

ASSINATURA DA PESSOA OBTENDO CONSENTIMENTO DATA

APPENDIX E

E1: Demographic questionnaire - English

Date:
Subject Number:

Name: ____
Phone Number: (Home)__________________ (Work)____________________
Best Hours to be Contacted by Phone: ________________________________
E-mail address: ___________________________________
Birth date: _____________________ Age ________

Are you currently a student? _________________
Last Grade Level Completed: ________________

Male _______ Female ________

Ethnicity, circle one (optional):
Hispanic or Latino   Not Hispanic or Latino   Prefer Not to Answer

Race, circle one (optional):
American Indian / Alaska Native   Asian   Native Hawaiian / Other Pacific Islander
Black / African American   White   More Than One Race
Prefer Not to Answer

Are you a native Portuguese speaker? _______
Do you speak English as a second language? _______

Right Handed _______   Left Handed _______
Glasses _________   Contacts _________   None _______

May we contact you about participating in future experiments? _______________

Possible Restrictions (Please write yes or no next to each one):
Are you less than 18 years old?
Are you claustrophobic?
Do you have a cardiac pacemaker?
Aneurysm clip?   Cochlear implant?
IUD?   Shrapnel?
History of metal fragments in the eyes?   Neurostimulators?
Pregnant?   300 lbs. or greater?
Permanent retainers or braces?
Non-removable body piercing?

E2: Demographic questionnaire – Portuguese

Data:
Número do Participante:

Nome: ____
Número de telefone: (Casa)_______________ (Trabalho)___________________
Melhor horário para ser contatado por telefone: __________________________
Endereço de e-mail: ____
Data de nascimento: ______________________ Idade ________

Você é estudante atualmente?_________________
Último nível concluído: ________________

Homem _______ Mulher ________

Etnia, escolha uma (opcional):
Hispânico ou Latino Não-hispânico ou Latino Prefiro não responder

Raça, circule uma (opcional):
Índio Americano/ Nativo do Alasca Asiático Nativo do Havaí / Outra ilha do Pacífico
Negro / Africano-americano Branco Mais de uma raça
Prefiro não responder

Você é falante nativo de português? _______
Você fala inglês como segunda língua? _______

Destro _______ Canhoto _______
Óculos _________ Lentes de contato _________ Nada ________

Podemos contatá-lo para participar de experimentos futuros?
____

Possíveis Restrições (Por favor, escreva sim ou não ao lado de cada pergunta):
Tem menos de 18 anos de idade?
Você é claustrofóbico?
Você tem um marca-passo cardíaco?
Clipe de aneurisma? Implante coclear?
DIU? Fragmento de metal?
Histórico de fragmentos de metal nos olhos? Neuroestimuladores?
Grávida? Pesa mais de 137 kg?
Retentores / aparelho nos dentes?
Piercing não-removível?

APPENDIX F

F1: Handedness questionnaire – English

Date:
Subject Number:

Please indicate your preferences in the use of hands in the following *activities by putting + in the appropriate column*. Where the preference is so strong that you would never try to use the other hand unless absolutely forced to, *put* ++. If in any case you are really indifferent *put + in both columns*.

Some of the activities require both hands. In these cases the part of the task, or object, for which hand preference is wanted is indicated in brackets.

Please try to answer all the questions, and only leave a blank if you have no experience at all of the object or task.

		LEFT	RIGHT
1	Writing		
2	Drawing		
3	Throwing		
4	Scissors		
5	Toothbrush		
6	Knife (without fork)		
7	Spoon		
8	Broom (upper hand)		
9	Striking Match (match)		
10	Opening box (lid)		
i	Which foot do you prefer to kick with?		
ii	Which eye do you use when using only one!		

F2: Handedness questionnaire – Portuguese

Data:
Número do Participante:

Por favor indique suas preferências para o uso de suas mãos nas seguintes *atividades colocando + na coluna apropriada*. Onde a preferência é tão forte que você nunca usaria a outra mão, a menos que seja forçado a fazer, *coloque* ++. No caso de ser indiferente, *coloque + nas duas colunas*.

Algumas das atividades requerem as duas mãos. Nestes casos, indicamos em parênteses a parte da tarefa ou o objeto da qual queremos saber a preferência.

Por favor tente responder todas as questões e apenas deixe em branco se você não tiver experiência com a tarefa ou o objeto.

		ESQUERDA	DIREITA
1	Escrever		
2	Desenhar		
3	Jogar algo		
4	Tesoura		
5	Escova de dentes		
6	Faca (sem garfo)		
7	Colher		
8	Vassoura (mão de cima)		
9	Acender fósforo (fósforo)		
10	Abrir caixa (tampa)		
i	Qual pé você prefere usar para chutar?		
ii	Qual olho você usa quando apenas pode usar um?		

APPENDIX G

G1: Instructions – English

Thinking about familiar concepts

This study investigates how accurately the concept someone is thinking about can be identified from its brain activation signature. We have already had good success identifying thoughts of individual concepts (like **gardener** or **pear**) from their fMRI signatures. This new study examines whether word concepts can be identified when they are encountered in the context of simple sentences, like: **The gardener eats the pear**.

In this experiment, you will be shown sentences to read, and they will appear one phrase at a time. As the sentence gradually unfolds, your job is to think about each concept and its main properties. For example, if the phrase **The gardener** were presented, you might think about:

- a typical activity of a gardener, like pruning a shrub
- a typical context in which a gardener might be found, like standing next to a bush,
- a typical goal, like enhancing the plant's health

Here is an example of some **good** properties for the sentence **The engineer gave a book to the student**:

The engineer	gave	a book	to the student
educated holding tools on a bridge	extending hand holding something generosity	thick and heavy worn cover author on spine	young wearing a backpack at a college

Notice how easy it is to conjure up a vivid mental representation of each of these phrases both by themselves and in the context of the sentence. Also notice how each property is very closely related to the phrase, so that we could almost guess the phrase by simply looking at the properties. And here is an example of some **bad** properties:

The engineer	gave	a book	to the student
person on the job	gift card	rectangle brown	sitting on a couch eating ice cream

Notice how many of these properties may relate to the concepts, but are not specific enough to be **intrinsic properties**. For example, it's certainly possibly to find a student eating ice cream on a couch, but this is probably not the first thing you would think when you see the word student. Similarly, a gift card *is* something that you give, but we're looking for properties that summarize the **act** of giving.

In addition to the quality of your word properties, <u>it is very important that you think of the same properties of a concept each time you see it</u>. In order to get reliable data, we need you to think about each sentence <u>4 different times</u>, so we can take an average of the 4 activation patterns for the same concept. This is why your consistency in what you think is important.

When the individual phrases of a sentence are presented, think of the concept and its key, vivid properties, as we described above. When the next phrase of the sentence is presented, add that concept to your mental representation. For example, if the sentence was "The athlete throws the knife." You would first see "The athlete" and think about the properties of an athlete. Then when "throws" appears, you would think about an athlete throwing. Finally when knife appears, you will think of the athlete throwing the knife.

After the last phrase of the sentence, there will be an interval of time where there is nothing on the screen. Use this time to keep thinking of all the components of the sentence. After the blank interval, an X will appear on the screen. While the X is on the screen try to **relax and clear your mind**. After some time, the next sentence will appear. When you're ready to continue, we will head over to the simulator to practice the task. If you have any questions, please do not hesitate to ask.

G2: Instructions – Portuguese

Pensar em conceitos familiares

Este estudo investiga a representação de conceitos no cérebro. Um dos nossos objetivos é verificar o quão corretamente podemos usar a ativação cerebral para identificar o conceito sobre o qual alguém está pensando. Em estudos conduzidos em nosso laboratório, já conseguimos identificar com sucesso pensamentos acerca de conceitos individuais (como jardineiro ou pêra) a partir da ativação cerebral capturada pela ressonância magnética funcional (fMRI). Este novo estudo, o qual você foi convidado a participar, examina se os conceitos podem ser identificados quando eles se encontram no contexto de frases simples, como: **O jardineiro come a pêra**.

Neste experimento, frases serão apresentadas em partes, por exemplo, a frase **A menina é bonita** será mostrada da seguinte forma: primeiro **A menina**, depois **é** e por último **bonita**. À medida que a frase vai aparecendo gradualmente, pedimos que você pense em cada conceito e suas principais propriedades.

Por exemplo, ao ser apresentada a parte **O jardineiro** (da frase **O jardineiro come a pêra**), você pode pensar sobre:
• uma atividade típica de um jardineiro, como podar um arbusto;
• um contexto típico em que um jardineiro pode ser encontrado, como estar em um jardim trabalhando,
• um objetivo comum, como cuidar da planta e melhorar sua saúde.

Aqui você encontra uma lista com propriedades **boas** para a frase **O engenheiro deu um livro para o aluno**:

O engenheiro	deu	um livro	para o estudante
estudado segurando ferramentas em uma ponte	estendendo a mão segurando algo generosidade	grosso e pesado capa desgastada nome do autor escrito na lombada	jovem usando uma mochila na universidade

Observe como é fácil evocar uma representação mental vívida das palavras, tanto isoladas (uma por uma) como no contexto da frase. Perceba também como cada propriedade está intimamente relacionada com a frase de modo que quase poderíamos adivinhar a frase bastando observar as propriedades.

Aqui você encontra exemplos de propriedades **ruins**:

O engenheiro	deu	um livro	para o estudante
pessoa trabalhando	cartão-presente	retângulo marrom	sentado num sofá comendo sorvete

Observe como muitas dessas propriedades podem estar relacionadas com os conceitos, mas não são específicas o suficiente para serem **propriedades intrínsecas**. Por exemplo, é certamente possível encontrar um estudante tomando sorvete num sofá, mas isso provavelmente não é a primeira coisa na qual você pensa quando vê a palavra aluno. Da mesma forma, um cartão-presente *é* algo que você dá, mas estamos à procura de propriedades que resumem **o ato** de dar.

Além da qualidade das propriedades das palavras, é muito importante que você pense nas mesmas propriedades de um conceito cada vez que você vê-lo. A fim de obter dados confiáveis , é preciso que você pense sobre cada frase em 4 momentos diferentes para que possamos ter uma média dos 4 padrões de ativação para o mesmo conceito/frase. É por isso que é tão importante ser **consistente** (pensar nas mesmas propriedades cada vez que a palavra/conceito aparece).

Quando as partes de uma frase são apresentadas, pense no conceito e nas suas principais propriedades, propriedades vívidas, conforme descrito acima. Quando a próxima parte da frase é apresentada, adicione os conceitos dessa parte à sua representação mental. Por exemplo, se a frase fosse **O atleta joga a faca**, você veria primeiro **O atleta** e pensaria nas propriedades de um atleta. Quando **joga** aparecesse, você pensaria sobre um atleta arremessando algo. Finalmente, quando **a faca** aparecesse, você pensaria no atleta jogando a faca.

Após a última parte da frase, haverá um intervalo de tempo em que não aparecerá nada na tela. Use esse tempo para continuar pensando em todos os componentes da frase. Após esse intervalo 'em branco', um X aparecerá na tela. Enquanto o X estiver na tela tente relaxar e limpar sua mente. Depois de algum tempo, a frase seguinte será exibida.
Quando você estiver pronto para continuar, nós iremos para a sala do simulador para praticarmos a atividade. Se você tiver alguma dúvida, por favor, não hesite em perguntar.

APPENDIX H

H1: Recognition task sentences – English

Recognition sentences	
Sentence	**Valid**
The diplomat was wealthy.	1
The fish swam in the shallow pond.	0
The mouse lived in the wall.	0
The excited boy ran in the big yard.	0
The nurse helped the sick man.	0
The street was empty at night.	1
The jury watched the witness.	1
The family was happy.	1
The screen looked cracked.	0
The store seemed crowded.	0
The diplomat shouted at the soldier.	1
The manager read the newspaper.	0
The ambassador delivered the message to the leader.	0
The man hated milk.	0
The wealthy politician liked coffee.	1
The patient survived.	1
The hungry cow ate the tall grass.	0
The politician visited the family.	1
The gardener planted the tree.	0
The happy couple visited the embassy.	1
The group attended the noisy concert.	0
The woman left the restaurant after the storm.	1
The scientist spoke to the student.	1
The mayor listened to the voter.	1
The teacher felt sad.	0
The chef cooked the carrots.	0
The wealthy author walked into the office.	1
The electrician climbed into the attic.	0
The young author spoke to the editor.	1
The father heard the musician pluck the string.	0
The banker watched the peaceful protest.	1
The wealthy couple left the theater.	1
The street was dark.	1
The yellow bird flew over the field.	1
The flower was yellow.	1
The school was famous.	1

The veteran talked at the conference.	0
The group had arrived by noon.	0
The careful waitress poured the expensive wine.	0
The tourist went to the restaurant.	1
The mother loved the show.	0
The famous diplomat left the hospital.	1
The politician watched the trial.	1
The dog broke the television.	1
The diplomat negotiated at the embassy.	1
The commander listened to the soldier.	1
The strong hiker climbed the snowy mountain.	0
The witness spoke to the lawyer.	1
The clerk explained the product to the customer.	0
The new café had several customers.	0
The waiter prepared the dessert.	0
The article had an interesting title.	0
The magazine was yellow.	1
The tall painter fed the cat.	0
The skilled dentist cleaned the tooth.	0
The crowd had energy.	0
The soldier crossed the field.	1
The tired patient slept in the dark hospital.	1
The mechanic fixed the truck.	0
The senator argued at the important meeting.	0

1: the sentence is old, it appeared in the scanning session
0: the sentence is new, it did not appear in the scanning session

H2: Recognition task sentences – Portuguese

Recognition sentences	
Sentence	**Valid**
O diplomata era rico.	1
O peixe nadou na lagoa rasa.	0
O rato vivia na parede.	0
O garoto animado correu no pátio grande.	0
A enfermeira ajudou o homem doente.	0
A rua estava vazia à noite.	1
O júri observou a testemunha.	1
A família estava feliz.	1
A tela parecia rachada.	0
A loja parecia cheia.	0
O diplomata gritou com o soldado.	1
O gerente leu o jornal.	0
O embaixador entregou a mensagem ao líder.	0
O homem odiava leite.	0
O político rico gostava de café.	1
O paciente sobreviveu.	1
A vaca faminta comeu a grama alta.	0
O politico visitou a família.	1
O jardineiro plantou a árvore.	0
O casal feliz visitou a embaixada.	1
O grupo compareceu ao concerto barulhento.	0
A mulher saiu do restaurante depois da tempestade.	1
O cientista falou com o estudante.	1
O prefeito ouviu o eleitor.	1
O professor se sentiu triste.	0
O chefe cozinhou as cenouras.	0
O autor rico entrou no escritório.	1
O eletricista subiu no sótão.	0
O autor jovem falou com o editor.	1
O pai escutou o músico puxar a corda.	0
O banqueiro assistiu ao protesto pacífico.	1
O casal rico saiu do teatro.	1
A rua estava escura.	1
O pássaro amarelo sobrevoou o campo.	1
A flor era amarela.	1
A escola era famosa.	1
O veterano falou na conferência.	0
O grupo chegou ao meio-dia.	0

A garçonete cuidadosa serviu o vinho caro.	0
O turista foi ao restaurante.	1
A mãe amou o show.	0
O diplomata famoso deixou o hospital.	1
O político assistiu ao julgamento.	1
O cachorro quebrou a televisão.	1
O diplomata negociou na embaixada.	1
O comandante ouviu o soldado.	1
O forte alpinista escalou a montanha de neve.	0
A testemunha falou com o advogado.	1
O funcionário explicou o produto para o cliente.	0
O novo café tinha vários clientes.	0
O garçom preparou a sobremesa.	0
O artigo tinha um título interessante.	0
A revista era amarela.	1
O pintor alto alimentou o gato.	0
O dentista especializado limpou o dente.	0
A multidão tinha energia.	0
O soldado atravessou o campo.	1
O paciente cansado dormiu no hospital escuro.	1
O mecânico consertou o caminhão.	0
O senador discutiu na reunião importante.	0

1: the sentence is old, it appeared in the scanning session
0: the sentence is new, it did not appear in the scanning session

APPENDIX I

I1: Debriefing questions – English

Date:
Subject Number:
MRI Number:

DEBRIEFING

1. Was there anything that made you physically uncomfortable during the experiment? If so, what was it?

___

___

___

2. Is there anything else that kept you from doing the task as well as you otherwise could have?

___

___

___

3. Is there anything else that you might want us to note about any of the tasks?

___

___

___

4. Would you be interested in running in another fMRI experiment if the opportunity became available?

___

5. Was there a specific way you thought of each sentence?

___

___

___

6. Did you have time to think of each phrase?

___

___

___

7. Did the meaning of the sentence come together as you read it or at the end?

___

___

___

I1: Debriefing questions – Portuguese

Data:
Número do participante:
Número do fMRI:

QUESTIONÁRIO

1. Você se sentiu fisicamente desconfortável durante o experimento? Se sim, o que aconteceu?

____

____

____

2. Houve algo que atrapalhou a execução da tarefa da forma como você queria tê-la executado?

____

____

____

3. Há algo mais que você gostaria de nos alertar sobre qualquer uma das tarefas?

____

____

____

4. Você está interessado em participar de outro experimento com fMRI se a oportunidade aparecer?

____

5. Você pensou em cada frase de alguma maneira específica?

____

____

____

6. Você teve tempo para pensar em cada parte das frases?

____

____

____

7. O significado da frase veio junto conforme você lia a frase ou apenas ao final?

____

____

____

APPENDIX J

J1: RST instructions

READING SPAN TEST INSTRUCTIONS

You are going to perform the Reading Span Test in two languages: Portuguese and English. The instructions are the same and the dynamics of the test is very simple: a set of unrelated sentences will be presented to you on the computer screen. Each time a sentence is shown on the screen, read the sentence aloud and try to memorize the last word of that sentence. The sentences were divided into groups and separated by a screen with question marks on it. Each time this screen with question marks appears, you should search your memory and try to say to the researcher the last word of each sentence in that group, exactly in the same order that they were presented. The number of sentences in each group increases progressively, from two to six sentences in each set. To ensure you understand what you have to do, we have a training session.

INSTRUÇÕES TESTE DE CAPACIDADE DE LEITURA

Uma série de frases soltas será apresentada a você na tela do computador em português. Cada vez que uma dessas frases for mostrada, leia a frase em voz alta e tente memorizar a última palavra da frase. As frases foram divididas em grupos, separados por uma ficha com pontos de interrogação. Cada vez que uma ficha dessas aparecer, busque na memória e diga em voz alta todas as últimas palavras daquele grupo, exatamente na ordem em que foram mostradas. O número de frases em cada grupo vai aumentando progressivamente. Para que você possa entender o procedimento e tirar suas dúvidas, será feito um treinamento inicial.

J2: List of the RST sentences in English (adapted from Daneman & Carpenter, 1980)

TRAINING SESSION
1 - Due to his gross inadequacies, his position as director was terminated **abruptly**. (12 words)
2 - It is possible, of course, that life did not arise on the earth at **all**. (15 words)
3 - I wish there existed someone to whom I could say that I felt very **sorry**. (15 words)
4 - The poor lady was thoroughly persuaded that she was not long to survive this **vision**. (15 words)
5 - Jane's relatives had decided that her gentleman friend was not one of high **status**. (14 words)
6 - Without any hesitation, he plunged into the difficult mathematics assignment **blindly**. (11 words)
7 - The entire town arrived to see the appearance of the controversial political **candidate**. (13 words)
8 - After passing all the exams, the class celebrated for an entire week without **resting**. (14 words)
9 - According to the results of the survey, Robert Redford is the most liked Hollywood **star**. (15 words)

START
1 - The weather was unpredictable that summer so no one made plans too far in **advance**. (15 words)
2 – The devastating effects of the flood were not fully realized until months **later**. (13 words)
3 – In a moment of complete spontaneity, she developed a thesis for her **paper**. (13 words)
4 – At the conclusion of the musicians' performance, the enthusiastic crowd **applauded**. (11 words)
5 – They attended the theater habitually except for circumstances beyond their **control**. (11 words)
6 – The lumbermen worked long hours in order to obtain the necessary amount of **wood**. (14 words)
7 – The old lady talked to her new neighbor on her weekly walks from **church**. (14 words)
8 – There are days when the city where I live wakes in the morning with a strange **look**. (17 words)
9 – He laughed sarcastically and looked as if he could have poisoned me for my **errors**. (15 words)
10 – With shocked amazement and appalled fascination Marion looked at the **pictures**. (11 words)
11 – What would come after this day would be inconceivably different, would be real **life**. (14 words)
12 – He stood there at the edge of the crowd while they were singing, and he looked **bitter**. (17 words)
13 – John became annoyed with Karen's bad habits of biting her nails and chewing **gum**. (14 words)
14 – Circumstantial evidence indicated that there was a conspiracy to eliminate **him**. (11 words)
15 – To determine the effects of the medication, the doctor hospitalized his **patient**. (12 words)
16 – Her mother nagged incessantly about her lack of concern for the welfare of the **children**. (15 words)
17 – Without tension there could be no balance either in nature or in mechanical **design**. (14 words)
18 – In order to postpone the business trip, he canceled his engagements for the **week**. (14 words)
19 – The incorrigible child was punished brutally for his lack of respect for his **elders**. (14 words)
20 – The brilliant trial attorney dazzled the jury with his astute knowledge of the **case**. (14 words)
21 – I imagine that you have a shrewd suspicion of the object of my earlier **visit**. (15 words)
22 – I turned my memories over at random like pictures in a photograph **album**. (13 words)
23 – I'm not certain what went wrong but I think it was my cruel and bad **temper**. (16 words)
24 – Filled with these dreary forebodings, I fearfully opened the heavy wooden **door**. (12 words)
25 – Sometimes I get so tired of trying to convince him that I love him and shall **forever**. (17 words)
26 – When in trouble, children naturally hope for a miraculous intervention by a **superhuman**. (13 words)
27 – It was your belief in the significance of my suffering that kept me **going**. (14 words)
28 – The girl hesitated for a moment to taste the onions because her husband hated the **smell**. (16 words)
29 – The smokers were asked to refrain from their habit until the end of the **production**. (15 words)
30 – The young business executive was determined to develop his housing projects within the **year**. (14 words)
31 – Despite the unusually cold weather, the campers continued their canoe **trip**. (11 words)
32 – All students that passed the test were exempt from any further seminars that **semester**. (14 words)
33 – The entire construction crew decided to lengthen their work day in order to have **lunch**. (15 words)

34 – In comparison to his earlier works, the musician had developed a unique enthralling **style**. (14 words)
35 – The boisterous laughter of the children was disturbing to the aged in the **building**. (14 words)
36 – The sound of an approaching train woke him, and he started to his **feet**. (14 words)
37 – A small oil lamp burned on the floor and two men crouched against the wall, watching **me**. (17 words)
38 – The products of digital electronics will play an important role in your **future**. (13 words)
39 – One problem with this explanation is that there appears to be no defense against **cheating**. (15 words)
40 – Sometimes the scapegoat is an outsider who has been taken into the **community**. (13 words)
41 – I should not be able to make anyone understand how exciting it all **was**. (14 words)
42 – In a flash of fatigue and fantasy, he saw a fat Indian sitting beside a **campfire**. (16 words)
43 – The lieutenant sat beside the man with the walkie-talkie and stared at the muddy **ground**. (15 words)
44 – I will not shock my readers with a description of the cool-blooded butchery that **followed**. (15 words)
45 – The courses are designed as much for professional engineers as for amateur **enthusiasts**. (13 words)
46 – The taxi turned up Michigan Avenue, where they had a clear view of the **lake**. (15 words)
47 – The words of human love have been used by the saints to describe their vision of **God**. (17 words)
48 – It was shortly after this that an unusual pressure of business called me into **town**. (15 words)
49 – He pursued this theme, still pretending to seek for information to quiet his own **doubts**. (15 words)
50 – I was so surprised at this unaccountable apparition, that I was speechless for a **while**. (15 words)
51 – When at last his eyes opened, there was no gleam of triumph, no shade of **anger**. (16 words)
52 – He leaned on the parapet of the bridge and the two policemen watched him from a **distance**. (17 words)
53 – These splendid melancholy eyes were turned upon me from the mirror with a haughty **stare**. (15 words)
54 – He sometimes considered suicide but the thought was too oppressive to remain in his **mind**. (15 words)
55 – And now that a man had died, some unimaginably different state of affairs must come to **be**. (17 words)
56 – When I got to the big tobacco field I saw that it had not suffered **much**. (16 words)
57 – Here, as elsewhere, the empirical patterns are important and abundantly **documented**. (11 words)
58 – The intervals of silence grew progressively longer; the delays became very **maddening**. (12 words)
59 – Two or three substantial pieces of wood smoldered on the hearth, for the night was **cold**. (16 words)
60 – I imagined that he had been thinking things over while the secretary was with **us**. (15 words)

J3: List of the RST sentences in Portuguese (Tomitch, 2003; Bailer, 2011)

SESSÃO DE TREINO

1 - Caiu o número de profissionais que diziam querer ficar por muito tempo no atual **emprego**. (15 palavras, *Você S/A*, fevereiro de 2011, p.51)

2 - O consumo de proteínas estimula a produção de células dos tecidos ósseos e musculares, acelerando o **crescimento**. (17 palavras, *Superinteressante*, agosto de 2000, versão online)

3 - Adotar uma postura ética eleva tanto o nível de felicidade quanto ganhar um **aumento**. (14 palavras, *Superinteressante*, dezembro de 2010, versão online)

4 - De modo geral, os imigrantes vindos do Terceiro Mundo têm famílias mais numerosas que os **europeus**. (16 palavras, *Veja*, 24 de outubro de 2007, p.120)

5 - Descobriu-se que o grau de identificação com a equipe não tinha relação com as vitórias ou **derrotas**. (17 palavras, *Mente e Cérebro*, maio de 2011, p.41)

6 - Para construir a trama os atores passaram, durante dois meses, por um processo diretamente influenciado pelo **cinema**. (17 palavras, *Mente e cérebro*, maio de 2010, p.11)

7 - O açúcar é uma parte natural da vida humana desde os primórdios de nossa **existência**. (15 palavras, *Veja*, 24 de outubro de 2007, p.11-12)

8 - O consumo isolado de farinha de linhaça não vai baixar os tão desejados pontinhos da **balança**. (16 palavras, *Women's Health*, abril de 2010, p.46)

9 - Não se esqueça de incluir a cidade de onde escreve e telefone para **contato**. (14 palavras, *Mente e cérebro*, maio de 2010, p.7)

INÍCIO

1 - O intelsat-6 foi lançado em 1990, mas nunca funcionou – ficou numa órbita **errada**. (13 palavras, *Veja*, 20 de maio de 1992, p.63)

2 - A iniciativa deve partir da própria pessoa interessada em ter um corpo bonito e **saudável**. (15 palavras, *Veja SC*, 15 de abril de 1992, p.4)

3 - Ele é uma pessoa que gosta de contar a todos o que anda fazendo, nos mínimos **detalhes**. (17 palavras, *Mente e cérebro*, maio de 2010, p.44)

4 - As bactérias degradam as emulsões coloridas do filme, criando imagens que podem ser definidas como **futuristas**. (16 palavras, *Superinteressante*, fevereiro de 1992, p.14)

5 - A padronização agrícola, para atender aos consumidores, ameaça a diversidade biológica do mundo **vegetal**. (14 palavras, *Superinteressante*, julho de 1992, p.10)

6 - Os diálogos acontecem ao mesmo tempo, e cabe ao espectador escolher para onde dirigir sua **atenção**. (16 palavras, *Mente e cérebro*, maio de 2010, p.7)

7 - Para realizar as atividades cerebrais do pensamento, os neurônios tiram energia do oxigênio e da **glicose**. (14 palavras, *Superinteressante*, julho de 1992, p.10)

8 - O truque, portanto, é partir triunfante rumo ao objetivo antes do início da **partida**. (14 palavras, *Mente e cérebro*, maio de 2010, p.24)

9 - Cerca de 250 milhões de pessoas, ao redor do mundo, se encontram na mais profunda **depressão**. (16 palavras, *Superinteressante*, setembro de 1992, p.57)

10 - O repórter não deu grande importância à frase, mas esse parecia ser justamente o segredo do **sucesso**. (17 palavras, *Mente e cérebro*, maio de 2010, p.24)

11 - Uma manifestação estudantil ontem em Brasília foi marcada por atritos com a **polícia**. (13 palavras, *Folha de S. Paulo*, 17 de setembro de 1992)

12 - Mostra a capacidade do homem em transformar coisas simples em obras de arte, através da **dedicação**. (16 palavras, *Superinteressante*, setembro de 1992, p.3)

13 - A expressão refere-se à tentativa de conciliar o progresso com a preservação da **natureza**. (14 palavras, *Veja*, 3 de junho de 1992, p.34)

14 - Cada volume traz textos inéditos escritos por psicólogos e psicanalistas, todos especialistas no **assunto**. (14 palavras, *Mente e cérebro*, maio de 2010, p.8)

15 - Pesquisa do Sebrae aponta que o novo salário mínimo deve provocar uma onda de **demissões**. (15 palavras, *Folha de S. Paulo*, 17 de setembro de 1992)

16 - Se o Brasil pretende ir ao espaço sem pedir licença, não pode dispensar um programa de **foguetes**. (17 palavras, *Superinteressante*, setembro de 1992, p.10)

17 - O médico deve levar em conta a idade, número de filhos e saúde do **paciente**. (15 palavras, *Folha de S. Paulo*, 17 de setembro de 1992)
18 - Soube que o marido não ganhou o direito de protestar contra o abandono em momento tão **delicado**. (17 palavras, *Superinteressante*, setembro de 1992, p.4)
19 - Nós pedimos para o mundo falar e a mensagem soou alta, clara e extraordinariamente **perfeita**. (15 palavras, *Veja*, 3 de junho de 1992, p.98)
20 - A obra custou caro demais, a utilidade é incerta e o resultado final, **polêmico**. (14 palavras, *Veja*, 23 de setembro de 1992, p.60)
21 - É a primeira vez que se consegue em órbita a ovulação e fertilização de espécies **animais**. (16 palavras, *Veja*, 23 de setembro de 1992, p.61)
22 - Os fabricantes de microcomputadores estão criando produtos com novas tecnologias, a preços mais **atraentes**. (14 palavras, *Folha de S. Paulo*, 23 de setembro de 1992)
23 - Pesquisadores descobrem que o antílope das pradarias norte-americanas é o mais resistentes dos mamíferos **terrestres**. (15 palavras, *Superinteressante*, julho de 1992, p.37)
24 - O neandertal tinha testa curta e grossa, mandíbula forte, de queixo curto, e seus ossos eram **pesados**. (17 palavras, *Superinteressante*, julho de 1992, p.37)
25 - Reconhecer a importância da identidade social abre as portas para novas possibilidades de **reflexão**. (14 palavras, *Mente e Cérebro*, maio de 2011, p.43)
26 - Às vésperas do fim da reserva da informática, cresce a pressão por novos privilégios e **favores**. (16 palavras, *Veja*, 23 de setembro de 1992, p.80)
27 - Seu público eram as pessoas que olham muito para a pechincha e pouco para a **qualidade**. (16 palavras, *Veja*, 23 de setembro de 1992, p.83)
28 - O Brasil reforça sua presença no milionário clube da telefonia celular com o anúncio de novos **editais**. (17 palavras, *Veja*, 23 de setembro de 1992, p.85)
29 - Quando o cineasta dá rédea solta ao puro amor pelas imagens, o filme arrebata os **sentidos**. (16 palavras, *Folha de S. Paulo*, 23 de setembro de 1992)
30 - Na catarata, a vítima perde a visão gradualmente porque as células do cristalino tornam-se mais **opacas**. (16 palavras, *Superinteressante*, fevereiro de 1992, p.9)
31 - É difícil acreditar no acidente que interrompeu a arrancada do trem voador japonês, rumo às rotas **comerciais**. (17 palavras, *Superinteressante*, fevereiro de 1992, versão online)
32 - Os conservadores usaram e abusaram das teses de perversidade, da futilidade e da **ameaça**. (14 palavras, *Folha de S. Paulo*, 23 de setembro de 1992)
33 - Elas mostraram sinais de rotas das caravanas de mercadores, que levaram os pesquisadores à **cidade**. (15 palavras, *Superinteressante*, junho de 1992, p.10)
34 - Cartão-postal sob suspeita: radiação eletromagnética das antenas da Avenida Paulista pode afetar a saúde **humana**. (15 palavras, *Superinteressante*, junho de 1992, versão online)
35 - O investidor pode estar procurando a segurança do ouro, um investimento tradicional, neste momento de crise **política**. (17 palavras, *Folha de S. Paulo*, 23 de setembro de 1992)
36 - As fêmeas dos escorpiões só deixavam os abrigos dez vezes por ano, no **máximo**. (14 palavras, *Superinteressante*, agosto de 1992, p.8)
37 - O caso de Jill continua sendo estudado por especialistas que buscam soluções para doenças relacionadas à **memória**. (17 palavras, *Mente e cérebro*, maio de 2010, p.16)
38 - Os satélites ajudam os oceanógrafos a descobrir a temperatura da água em diversos locais do **planeta**. (16 palavras, *Superinteressante*, agosto de 1992, p.5)
39 - Nos casos de históricos de vida sedentária, evitar esportes anaeróbicos que exigem melhor condicionamento **físico**. (15 palavras, *VIP EXAME*, junho de 1992, p.19)
40 - Catástrofes à parte, a maior atração da viagem são a própria Galáxia e seus incríveis **habitantes**. (16 palavras, *Superinteressante*, agosto de 1992, p.24)
41 - O computador mostrou que, mesmo sem se quebrarem, alguns capacetes transmitem muita energia mecânica para a **cabeça**. (17 palavras, *Superinteressante*, agosto de 1992, p.30)
42 - A saúde instável do presidente serviu como outro elemento psicológico do ataque de nervos do **mercado**. (16 palavras, *Veja*, 23 de setembro de 1992)
43 - É a primeira vez que o Brasil vende tênis em quantidades expressivas no **exterior**. (14 palavras, *Veja*, 23 de setembro de 1992, p.84)
44 - O resto é luz do céu, claridade que desce da lua prateando a superfície **gelada**. (15 palavras, *VIP EXAME*, junho de 1992, p.44)

45 - O IBGE lançou um Atlas que mostra trezentas e três espécies de animais ameaçadas de **extinção**. (16 palavras, *Folha de S. Paulo*, 23 de setembro de 1992)
46 - O equipamento tem memória que permite dar ao usuário detalhes sobre eventuais defeitos em processos **industriais**. (16 palavras, *Folha de S. Paulo*, 23 de setembro de 1992)
47 - Os bosques de mangues, regados pelas marés, garantem comida farta para a fauna dos **oceanos**. (15 palavras, *Superinteressante*, maio de 1992, p.25)
48 - Hoje, quando o planeta é visto de cima pelos satélites, seus contornos não têm mais **segredo**. (16 palavras, *Superinteressante*, maio de 1992, p.34)
49 - Mesmo sem saber o índice de queda nas vendas, desvalorizou as ações da **empresa**. (14 palavras, *Veja*, 23 de setembro de 1992, p.86)
50 - Para os oitenta milhões de telespectadores brasileiros, a televisão significa lazer acessível e **barato**. (14 palavras, *Veja*, 23 de setembro de 1992, p.92)
51 - É preciso desmontar os motores em terra para prever as falhas, trabalho que consome tempo e **dinheiro**. (17 palavras, *Superinteressante*, julho de 1992, p.10)
52 - O paciente precisa de ressuscitação cardiorrespiratória o mais rápido possível, feita por pessoas **treinadas**. (14 palavras, *Folha de S. Paulo*, 28 de setembro de 1992)
53 - Segundo Senna, a chuva fez com que o desgaste dos pneus fosse excessivo na **corrida**. (15 palavras, *Folha de S. Paulo*, 28 de setembro de 1992)
54 - O povo com certeza irá ocupar as ruas para mostrar aos deputados o que querem seus **eleitores**. (17 palavras, *Folha de S. Paulo*, 28 de setembro de 1992)
55 - O telefone celular pode ser usado em qualquer ponto da cidade coberto por uma **célula**. (15 palavras, *Folha de S. Paulo*, 28 de setembro de 1992)
56 - Grandes quantidades de sal tornam a água mais pesada ou densa, diminuindo, em consequência, seu **volume**. (16 palavras, *Superinteressante*, julho de 1992, p.17)
57 - Como seres civilizados, deixamos as cavernas nas últimas glaciações, no início da Idade da Pedra **Polida**. (16 palavras, *Superinteressante*, agosto de 1992, p.73)
58 - A desvalorização é o que mais dói no orgulho nacional e no bolso de suas **vítimas**. (16 palavras, *Veja*, 23 de setembro de 1992, p.78)
59 - Não existe uma regra para definir a melhor hora para dar uma pausa no **trabalho**. (15 palavras, *Você S/A*, fevereiro de 2011, p.78)
60 - Os efeitos do sal na pressão das artérias dependem de outros minerais no **organismo**. (14 palavras, *Superinteressante*, fevereiro de 1992, p.15)

J4: RST answersheet – test in English

Date:
Subject Number:

READING SPAN TEST: ENGLISH

Training session

2 = _______________ _______________

3 = _______________ _______________ _______________

4 = _______________ _______________ _______________ _____________

Start

Sets of 2 sentences

1º set	2º set	3º set

Sets of 3 sentences

1º set	2º set	3º set

Sets of 4 sentences

1º set	2º set	3º set

Sets of 5 sentences

1º set	2º set	3º set

Sets of 6 sentences

1º set	2º set	3º set

J5: RST answersheet – test in Portuguese

Data:
Número do participante:

READING SPAN TEST: PORTUGUESE

Sessão de treino

2 = _______________ _______________

3 = _______________ _______________ _______________

4 = _______________ _______________ _______________ _____________

Início

Conjuntos de 2 frases

1º set	2º set	3º set

Conjuntos de 3 frases

1º set	2º set	3º set

Conjuntos de 4 frases

1º set	2º set	3º set

Conjuntos de 5 frases

1º set	2º set	3º set

Conjuntos de 6 frases

1º set	2º set	3º set

J6: Questionnaire applied after the execution of the RST in the two languages

Date:
Subject Number:

WORKING MEMORY QUESTIONNAIRE

1) You have just completed the Reading Span Test in two languages. Indicate how you felt while performing the tests (you can choose more than one option):
( ) comfortable ( ) challenged ( ) nervous ( ) exhausted
If you felt anything different from the options above, use the lines below to express how you felt during the tests. ____________________________________
____

2) Comparing the tests in the two languages, mark the option that best expresses what you think:
( ) the test in Portuguese was easier than in English.
( ) the test in Portuguese was more difficult than in English.
Do you think that proficiency in the languages may have played a role in your performance? If so, why? ____
____
____

3) If you used some strategy(ies) to memorize the last words of each sentence, describe it (them) in the lines below.
____
____
____
____
____
____
____

4) Is there anything else you would like to comment on? ____________________
____
____
____

J7: Questionnaire applied after the execution of the RST – monolinguals

Data:
Número do Participante:

QUESTIONÁRIO - MEMÓRIA DE TRABALHO

1) Você acabou de completar o teste de Capacidade em Leitura em português. Indique como você se sentiu ao realizar o teste (você pode escolher mais de uma opção):

( ) confortável
( ) desafiado
( ) nervoso
( ) cansado

Se você sentiu alguma coisa diferente das opções acima, use as linhas abaixo para expressar como você se sentiu durante o teste. ________________________
____
____
____

2) Se você usou alguma estratégia para memorizar a última palavra de cada frase, descreva-a(as) nas linhas abaixo. ________________________________
____
____
____
____
____

3) Tem algo mais que você gostaria de comentar ou sugerir?
____
____
____

APPENDIX K

K1: Adapted version of the reading section of the TOEFL test of proficiency

Date:
Subject Number:

Proficiency Test in English

Adapted from TOEFL [*Test of English as a Foreign Language*] Practice Test

Dear participant,

The task you are being asked to perform is a proficiency test in English. The test aims at assessing your skills of English use in terms of reading, writing, listening and speaking. However, for the purposes of this study, you are being asked to complete only the section on reading comprehension.

Just for the record, the TOEFL test is accepted and recognized worldwide. It is used among one of the criteria of admission to universities and programs in the English language (www.toeflgoanywhere.org).

Reading Comprehension Section

Directions: These questions measure your ability to understand an academic passage in English. You will read one passage and answer questions on the basis of what is *stated* or *implied* in the text. You have 35 minutes to read the passage and answer the questions.

Meteorite Impact and Dinosaur Extinction

There is increasing evidence that the impacts of meteorites have had important effects on Earth, particularly in the field of biological evolution. Such impacts continue to pose a natural hazard to life on Earth. Twice in the twentieth century, large meteorite objects are known to have collided with Earth.

If an impact is large enough, it can disturb the environment of the entire Earth and cause an ecological catastrophe. The best-documented such impact took place 65 million years ago at the end of the Cretaceous period of geological history. This break in Earth's history is marked by a mass extinction, when as many as half the species on the planet became extinct. While there are a dozen or more mass extinctions in the geological record, the Cretaceous mass extinction has always intrigued paleontologists because it marks the end of the age of the dinosaurs. For tens of millions of years, those great creatures had flourished. Then, suddenly, they disappeared.

The body that impacted Earth at the end of the Cretaceous period was a meteorite with a mass of more than a trillion tons and a diameter of at least 10 kilometers. Scientists first identified this impact in 1980 from the worldwide layer of sediment deposited from the dust cloud that enveloped the planet after the impact. This sediment layer is enriched in the rare metal iridium and other elements that are relatively abundant in a meteorite but very rare in the crust of Earth. Even diluted by the terrestrial material excavated from the crater, this component of meteorites is easily identified. By 1990 geologists had located the impact site itself in the Yucatán region of Mexico. The crater, now deeply buried in sediment, was originally about 200 kilometers in diameter.

This impact released an enormous amount of energy, excavating a crater about twice as large as the lunar crater Tycho. The explosion lifted about 100 trillion tons of dust into the atmosphere, as can be determined by measuring the thickness of the sediment layer formed when this dust settled to the surface. Such a quantity of material would have blocked the sunlight completely from reaching the surface, plunging Earth into a period of cold and darkness that lasted at least several months. The explosion is also calculated to have produced vast quantities of nitric acid and melted rock that sprayed out over much of Earth, starting widespread fires that must have consumed most terrestrial forests and grassland. Presumably, those environmental disasters could have been responsible for the mass extinction, including the death of the dinosaurs.

Several other mass extinctions in the geological record have been tentatively identified with large impacts, but none is so dramatic as the Cretaceous event. But even without such specific documentation, it is clear that impacts of this size do occur and that their results can be catastrophic. What is a catastrophe for one group of living things, however, may create opportunities for another group. Following each mass extinction, there is a sudden evolutionary burst as new species develop to fill the ecological niches opened by the event.

Impacts by meteorites represent one mechanism that could cause global catastrophes and seriously influence the evolution of life all over the planet. According to some estimates, the majority of all extinctions of species may be due to such impacts. Such a perspective fundamentally changes our view of biological evolution. The standard criterion for the survival of a species is its success in competing with other species and adapting to slowly changing environments. Yet an equally important criterion is the ability of a species to survive random global ecological catastrophes due to impacts.

Earth is a target in a cosmic shooting gallery, subject to random violent events that were unsuspected a few decades ago. In 1991 the United States Congress asked NASA to investigate the hazard posed today by large impacts on Earth. The group conducting the study concluded from a detailed analysis that impacts from meteorites can indeed be hazardous. Although there is always some risk that a large impact could occur, careful study shows that this risk is quite small.

1. In paragraph 2, why does the author include the information that dinosaurs had flourished for tens of millions of years and then suddenly disappeared?

    a. To support the claim that the mass extinction at the end of the Cretaceous is the best-documented of the dozen or so mass extinctions in the geological record

    b. To explain why as many as half of the species on Earth at the time are believed to have become extinct at the end of the Cretaceous

    c. To explain why paleontologists have always been intrigued by the mass extinction at the end of the Cretaceous

    d. To provide counter evidence that an impact cannot be large enough to disturb the environment of the entire planet and cause an ecological disaster

2. Which of the following can be inferred from paragraph 3 about the location of the meteorite impact in Mexico?

    a. The location of the impact site in Mexico was kept secret by geologists from 1980 to 1990.

    b. It was a well-known fact that the impact had occurred in the Yucatán region.

    c. Geologists knew that there had been an impact before they knew where it had occurred.

    d. The Yucatán region was chosen by geologists as the most probable impact site because of its climate.

3. According to paragraph 3, how did scientists determine that a large meteorite had impacted Earth?

    a. They discovered a large crater in the Yucatán region of Mexico.

    b. They found a unique layer of sediment worldwide.

    c. They were alerted by archaeologists who had been excavating in the Yucatán region.

    d. They located a meteorite with a mass of over a trillion tons.

4. According to paragraph 4, all of the following statements are true of the impact at the end of the Cretaceous period EXCEPT:

    a. A large amount of dust blocked sunlight from Earth.

    b. Earth became cold and dark for several months.

    c. New elements were formed in Earth's crust.

    d. Large quantities of nitric acid were produced.

5. The word "perspective" on line 47 is closest in meaning to:

    a. sense of values

    b. point of view

    c. calculation

    d. complication

6. Paragraph 6 supports which of the following statements about the factors that are essential for the survival of a species?

    a. The most important factor for the survival of a species is its ability to compete and adapt to gradual changes in its environment.

    b. The ability of a species to compete and adapt to a gradually changing environment is not the only ability that is essential for survival.

    c. Since most extinctions of species are due to major meteorite impacts, the ability to survive such impacts is the most important factor for the survival of a species.

    d. The factors that are most important for the survival of a species vary significantly from one species to another.

7. Which of the sentences below best expresses the essential information in the following sentence? Incorrect choices change the meaning in important ways or leave out essential information.

Earth is a target in a cosmic shooting gallery, subject to random violent events that were unsuspected a few decades ago.

    a. Until recently, nobody realized that Earth is exposed to unpredictable violent impacts from space.

    b. In the last few decades, the risk of a random violent impact from space has increased.

    c. Since most violent events on Earth occur randomly, nobody can predict when or where they will happen.

    d. A few decades ago, Earth became the target of random violent events originating in outer space.

8. According to the passage, who conducted investigations about the current dangers posed by large meteorite impacts on Earth?

    a. Paleontologists

    b. Geologists

    c. The United States Congress

    d. NASA

9. Look at the four letters (**A**, **B**, **C**, and **D**) that indicate where the following sentence could be added to the passage in paragraph 6.

This is the criterion emphasized by Darwin's theory of evolution by natural selection.

Where would the sentence best fit?

Impacts by meteorites represent one mechanism that could cause global catastrophes and seriously influence the evolution of life all over the planet. **(A)** According to some estimates, the majority of all extinctions of species may be due to such impacts. **(B)** Such a perspective fundamentally changes our view of biological evolution. **(C)** The standard criterion for the survival of a species is its success in competing with other species and adapting to slowly changing environments. **(D)** Yet an equally important criterion is the ability of a species to survive random global ecological catastrophes due to impacts.

Choose the place where the sentence fits best.

a. Option A b. Option B c. Option C d. Option D

10. An introductory sentence for a brief summary of the passage is provided below. Complete the summary by selecting the THREE answer choices that express the most important ideas in the passage. Some sentences do not belong in the summary because they express ideas that are not presented in the passage or are minor ideas in the passage.

Write your answer choices in the spaces where they belong. You can simply write in each line the number of the answer choice or the whole sentence.

Scientists have linked the mass extinction at the end of the Cretaceous with a meteorite impact on Earth.
•
•
•

Answer choices

(1) Scientists had believed for centuries that meteorite activity influenced evolution on Earth.

(2) The site of the large meteorite impact at the end of the Cretaceous period was identified in 1990.

(3) There have also been large meteorite impacts on the surface of the Moon, leaving craters like Tycho.

(4) An iridium-enriched sediment layer and a large impact crater in the Yucatán provide evidence that a large meteorite struck Earth about 65 million years ago.

(5) Large meteorite impacts, such as one at the end of the Cretaceous period, can seriously affect climate, ecological niches, plants, and animals.

(6) Meteorite impacts can be advantageous for some species, which thrive, and disastrous for other species, which become extinct.

Space reserved for the researcher:

____

APPENDIX L

L1: Language Background Questionnaire – bilinguals

Date:
Subject Number:

LANGUAGE BACKGROUND QUESTIONNAIRE

Learning experience:

1) What age were you when you started learning/studying English? _____________
2) In which country was it? ____

3) As regards the way you learned English, mark all the options that apply to you:
( ) formally at regular school
( ) formally at language institutes
( ) private classes
( ) watching movies or TV
( ) listening to music
( ) other. Specify ____

4) How many years have you been living in the US? _________________________
5) Have you lived in an English speaking country before? _____________________
If so, for how long? _______________________

6) Is there any other detail you would like to describe about your English learning experience? ____
____
____

Current use of English:

7) How much time of your day do you usually use English (speaking, listening, reading and writing)? ( ) all day long ( ) _______ hours

8) What kind of material do you usually read in English?
( ) academic material ( ) magazines ( ) books
( ) newspapers ( ) websites ( ) other. Specify _____

9) How much time of your day do you usually spend reading in English?
( ) less than 1 hour ( ) from 1 to 2 hours
( ) 2 to 4 hours ( ) more than 4 hours

10) How do you rate your proficiency in English today?

Reading:	☐ excellent	☐ good	☐ average	☐ poor	☐ not at all
Listening:	☐ excellent	☐ good	☐ average	☐ poor	☐ not at all
Speaking:	☐ excellent	☐ good	☐ average	☐ poor	☐ not at all
Writing:	☐ excellent	☐ good	☐ average	☐ poor	☐ not at all

11) Have you ever taken any standardized tests for English language proficiency? ________________ If so, which test(s) (TOEFL, IELTS)?

____________________Do you remember your score? ____________ And when did you take it? ____
____

Current use of Portuguese:

12) How much time of your day do you usually use Portuguese (speaking, listening, reading and writing)? ( ) all day long ( ) _______ hours

13) What kind of material do you usually read in Portuguese?
( ) academic material ( ) magazines ( ) books
( ) newspapers ( ) websites ( ) other. Specify _____

14) How much time of your day do you usually spend reading in Portuguese?
( ) less than 1 hour ( ) from 1 to 2 hours ( ) 2 to 4 hours
( ) more than 4 hours ( ) I am not reading anything in Portuguese currently.

Experience with other languages:

15) Do you speak any other language(s) besides Portuguese and English? ________
If so, what language(s)? ____
Do you consider yourself proficient in this language(s)? ______________________
____

16) Is there anything you would like to comment on about learning a second/third language?
____
____
____

L2: Language Background Questionnaire – monolinguals

Data:
Número do participante:

QUESTIONÁRIO SOBRE EXPERIÊNCIA LINGUÍSTICA

1) Onde você nasceu e cresceu? ____

2) Você teve contato com a língua portuguesa a sua infância toda, inclusive na escola, certo? ____

3) Você aprendeu inglês na escola? Teve aulas desde que série? Já fez cursos de inglês?
____
____
____
____

4) Você gostaria de comentar algo sobre sua experiência com a língua inglesa na escola? ____
____
____
____
____
____

5) Você já tentou aprender outra língua? Quando? _________________________
____

6) Você já morou em um país de língua inglesa antes? Se sim, especifique por quanto tempo.
____
____

7) Qual motivo levou você a vir morar nos EUA mesmo sem ter o conhecimento do idioma? Você pretende aprender inglês no futuro? Por quê?
____
____
____
____
____