PSICO
v. 39, n. 2, pp. 131-138, abr./jun. 2008

Neuroimaging of the bilingual brain: evidence and research methodology

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ABSTRACT

Given that nowadays more than half of the world's population is bilingual, the study of the neural basis of bilingual language processing has become a relevant and founding topic in the recent field of neuropsycholinguistics. This article has two main aims: 1) to discuss some methodological aspects related to the development of neuroimaging studies on language processing in the bilingual brain, and 2) to review neuroimaging data on language processing considering individual factors which have characterized the literature in bilingualism so far, for their impact on language architecture in the bilingual brain. Several studies have provided data on the role of age of acquisition, proficiency level, chronological age, learning method and language use on language organization in the bilingual brain. The variety of methodological approaches used and the lack of control of the various factors that can influence bilingual language processing have made it hard to draw conclusions on language circuitry in bilinguals. This discussion intends to contribute for the debate on the theoretical and methodological bases of the neurofunctional organization of languages in the bilingual brain.

Keywords: Bilingualism; neuroimaging; language; neuropsychology; neuropsycholinguistics.

RESUMO

Neuroimagem do cérebro bilíngüe: evidências e metodologia de pesquisa

Atualmente mais da metade da população mundial é bilíngüe, sendo o estudo do processamento lingüístico e de seus correlatos cerebrais em indivíduos bilíngües um tópico relevante e inovador na recente área da neuropsicolingüística. Este artigo tem dois objetivos: 1) discutir alguns aspectos metodológicos relacionados ao desenvolvimento de investigações com técnicas de neuroimagem sobre o processamento da linguagem no cérebro bilíngüe e 2) revisar evidências de neuroimagem sobre o processamento lingüístico considerando fatores individuais que têm caracterizado a literatura acerca do bilingüismo, por seu importante papel na representação cerebral bilíngüe da linguagem. Muitos estudos têm mostrado dados sobre a relação entre idade de aquisição, nível de proficiência, idade cronológica, uso de linguagem e forma de exposição às línguas na organização da linguagem no cérebro bilíngüe. A grande variabilidade de métodos de investigação e um controle metodológico nem sempre criterioso tem tornado difícil a generalização de conclusões sobre uma circuitaria cerebral da linguagem em bilíngües. A presente discussão deve contribuir para o debate dos fundamentos teóricos e metodológicos da organização neurofuncional da linguagem no cérebro bilíngüe.

Palavras-chave: Bilingüismo; neuroimagem; linguagem; neuropsicologia; neuropsicolingüística.

RESUMEN

Neuroimagen del cerebro bilíngüe: evidencia e investigación metodológica

En la actualidad más de la mitad de la población mundial es bilíngüe, el estudio de las bases neuronales del procesamiento del lenguaje bilíngüe se ha vuelto un tópico relevante y novedoso en la reciente área de psicolongüística. Este artículo tiene dos puntos principales: 1) discutir algunos aspectos metodológicos relacionados al desarrollo de estudios con técnicas de neuroimagen sobre el procesamiento del lenguaje del cerebro bilíngüe y 2) revisar evidencias de neuroimagen sobre el procesamiento lingüístico considerando factores individuales que han caracterizado a la literatura en el bilingüismo, por su importante papel en la representación cerebral bilíngüe del lenguaje. Algunos estudios han provisto de datos sobre la relación entre la edad de adquisición, nível de proficencia, edad cronológica, método de aprendizaje y uso del lenguaje y organización del lenguaje en el cerebro bilígüe. La gran variedad en los procesos metodológicos y el control de varios factores que pueden influenciar en el procesamiento del lenguaje en el bilígüe han dificultado generalizar conclusiones sobre un circuito cerebral del lenguaje en bilíngües. Esta discución pretende contribuir al debate de los fundamentos teóricos de la organización neurofuncional del lenguaje en el cerebro bilíngüe.

Palabras clave: Neuroimagen; lenguaje; neuropsicología; neuropsicolingüística.

INTRODUCTION

This paper discusses the issue of bilingualism within the frame of neuropsychology, especially regarding one of its related fields, neuropsycholinguistics. Its aims are the following: a) to discuss methodological aspects related to the development of neuroimaging studies on language processing in the bilingual brain, b) to summarize important neuroimaging data on language processing regarding the impact of individual factors on the bilingual brain. These two goals are very relevant when the

achievement of a consistent theoretical framework on language organization in the bilingual (and multilingual) brain is intended.

In searching to characterize "bilinguals" and "bilingualism", researchers define these terms in distinct ways, depending upon the degree of language mastering considered to be necessary to an individual be characterized as a bilingual. In the present article, the definition adopted is that one proposed by Grosjean (1994), according to which the term 'bilingual' refers to an individual who uses two or more languages or dialects in his or her everyday life, regardless of the context of use. Taking this definition into account, more than half of the world can be considered bilingual (Giussani, Roux, Lubrano, Gaini and Bello, 2007).

Bilinguals can be grouped by reference to two criteria: a) age of second language (L2) acquisition, and b) ways in which the words of the two languages relate to underlying concepts. The first typology refers to simultaneous, early or native bilinguals, who learn their first language or mother tongue (L1) and L2 simultaneously and during infancy, and successive or late bilinguals, who learn their L1 and L2 successively, at different times (Paradis, 2001, 2004). The second typology, proposed by Weinreich (1953), distinguishes three different groups of bilinguals: compound, coordinate, and subordinate. Coordinate bilinguals learn the languages in two distinguished contexts (for instance, home and school), so they would have two semantic systems and two codes. Compound bilinguals learn L1 and L2 in the same context, so they would have a single semantic system but two codes to access it. Finally, subordinate bilinguals learn the L2 by reference to the L1, generally via translation.

Research on bilinguals' language processing has been aided by the emergence of increasingly sophisticated neuroimaging techniques, such as functional magnetic resonance imaging (fMRI), positron emission topography (PET), magnetoencephalography (MEG), evoked response potentials (ERP), functional near-infrared spectroscopy (fNIRS), among others, which have allowed researchers to acquire *in vivo* brain images of the order of seconds or even milliseconds. By the use of these techniques, researchers have been able to test hypotheses on the neurofunctional organization of the brain while individuals produce and understand language, and have examined the role of cognitive components (such as memory and attention control) on this processing.

Given that bilinguals represent a very heterogeneous group, strict selection criteria for their participation in research is required. Moreover, special attention needs to be paid when comparing data from different neuroimaging studies.

The section that follows focus on methodological issues to be considered when designing, implementing and interpreting research data from neuroimaging studies on bilingual language processing.

1 METHODOLOGICAL ISSUES IN NEUROIMAGING RESEARCH ON BILINGUALS' LANGUAGE PROCESSING

The development of a neuropsycholinguistic theory on language processing in bilinguals requires the analysis of experimental data resulting from a relevant number of studies, with methodological equivalence in terms of experimental design and samples' features. Neuroimaging studies on bilingualism have investigated both comprehension and production, and have used a wide variety of experimental designs, tasks and criteria for participants' recruitment. This diversity can be informative; however, it is also a challenge for drawing general conclusions from the data. This section discusses on the factors to be considered and controlled when designing research on the neural substrate of language processing in bilinguals. The aspects to be discussed refer to 1) task typology, design and presentation, 2) language typology, oral or written modalities, 3) neurocognitive components linked to language processing, and 4) individual aspects in bilingualism.

1.1 Task typology, design and presentation

Regarding experimental tasks, it has already been acknowledged that task complexity influences the demand on cognitive resources for processing (Démonet, Thierry and Cardebat, 2005). Therefore, depending on the complexity of the experimental task and on the complexity of psycholinguistic variables involved in task completion, a wide range of neuroimaging results may be obtained.

More specifically, in the case of tasks demands, the amount of complexity can be controlled by manipulating instruction demands. For instance, the passive reading of a text will demand the recruitment of brain regions which may not be the same as those recruited when the participant is told to read the text for answering questions about it afterwards (Tzourio, Nkanga-Ngila and Mazoyer, 1998). The same applies to overt or covert syntactic or semantic judgments of sentences. The variability in tasks demands imposes a difficulty for grouping studies by reference to the specific linguistic aspect investigated, and consequently for drawing conclusions about this processing. Although these issues apply to studies with monolingual populations as well, the impact of these factors on the understanding of language processing by bilinguals is

further challenged by the variety of language combinations and the degree of overlap between the structural properties of these languages.

Regarding the complexity of psycholinguistic variables, several factors may concur for determining complexity level. In the case of the sentence level, for example, these factors include sentence structure (single, compound or complex sentences), semantic and syntactic processing demands, and literality, among others; at the word level, word frequency, imageability, word length and prototypicality are some of the aspects known to modulate processing (Friederici, Fiebach, Schlesewsky, Bornkessel and von Cramon, 2006).

Still in relation to task presentation, an important aspect, although very much neglected, is the language status of the tester, the person in charge of conducting the experiment, who directly interacts with the participant. More specifically, according to Grosjean (1999), data brought by experimental studies (including neuroimaging ones) may be affected by the fact of the tester himself/herself being or not a bilingual. This may cause interference in the results because as soon as the participant notices the possibility of communicating with the tester in a determined language, the likeliness of language switching (from L1 to L2 and vice-versa) and mixing (borrowing structural items from one language to another) increases. In a monolingual situation, when the tester masters only one of the two languages whose processing is going to be examined, mixing and switching are less likely to occur.

1.2 Language typology

A reduced number of studies reported in the literature in bilingualism has addressed the issue of language typology as a factor to determine neuroimaging patterns of brain activation. One of this studies was developed by Tan and colleagues (2003), who investigated the neural mechanisms of reading in Chinese (as L1) and in English (as L2), two languages with different phonological and orthographic systems, in order to analyze the effect of L1 typology on the acquisition of an L2. Differently from orthographic languages, written Chinese is based on logograms, single characters that represent a word. This fMRI study found that participants recruited the same brain regions when reading Chinese and English words; specifically, left middle frontal and posterior parietal gyri, two cortical regions involved in spatial information representation, spatial working memory and coordination of cognitive resources, such as central executive system, while different regions were recruited by English monolinguals. The authors concluded that the bilinguals were adopting their L1 strategies to L2 reading, and thus, that "language experience tunes the cortex".

The PET research conducted by Klein, Milner, Zatorre, Zhao and Nikelski (1999) compared verb generation and word repetition in Mandarin (L1) and English (L2 – late acquisition), and showed a shared neural substrate for both languages, in both types of tasks. Thus, their results are not consistent with those obtained by Tan and colleagues (2003), reported above, who found different areas of activation for word processing in both languages.

The inconsistencies in the results brought by these two illustrative studies show the necessity of further research on this topic. More investigation with the same neuroimaging techniques grouping oral language tasks and written language tasks are necessary to solve these nonconsensual findings.

1.3 Neurocognitive components linked to language processing

As it is the case with any other cognitive ability, language processing involves an array of cognitive functions, such as memory, attention and inhibitory control (for instance, the control for erroneous inferences) and cognitive flexibility (the revision and correction of a given hypothesis that has proven to be incorrect). Individual differences may modulate the participants' ability in recruiting each one of these capacities. Therefore, these abilities should be tested so as to make sure that discrepancies in performance on the language task are not motivated by differential abilities in other cognitive functions involved in the processing of the experimental task. Ideally, correlations between neuroimaging and behavioral data can be used to ponder the impact of a given cognitive ability on a particular language task, for instance, the impact of working memory capacity on the participant's performance in syntactic processing, depending upon the level of syntactic complexity (Suh et al., 2007).

1.4 Individual factors and bilingualism

Some individual factors, such as biological and socio-cultural features have been reported to influence language processing by bilinguals. Hence, it is essential that these factors are controlled as rigorously as possible to seek for sample homogeneity. Currently, participants are characterized by means of questionnaires (for example, the one proposed by Marian, Blumenfeld and Kaushanskaya, 2007), which gather information about the individuals' language experience and proficiency in writing, speaking, reading and oral comprehension, in each of the languages spoken.

Some of the most frequently issues assessed by questionnaires include the following: a) number of years speaking the languages, b) learning method (informal or formal), and number of years of formal education in the languages, c) degree of language exposure (at home, school, work, through media), and d) degree of proficiency in oral and written comprehension and expression, within each language. Questionnaires also test the participant's performance in grammaticality judgment tasks, reading fluency, oral comprehension, productive vocabulary and sound awareness (Marian et al., 2007). An example of questionnaire which was originally developed as a clinical tool is the short version of the Bilingual Aphasia Test, recently published by Muñoz and Marquardt (2008).

Socio-cultural background, ethnicity and socio-economic status are important factors to be considered to achieve sample homogeneity (Byalistok, 2006; Morton & Harper, 2007). According to Byalistok (2006), bilinguals are not randomly distributed in the groups of participants; instead, they are separated by their specific ethnic group or as immigrants. Data analysis has not always been concerned with considering the effect of the sample's nature and of their proficiency and frequency of language(s) use. As a consequence, in the past, judgments drawn from research on bilingual children have several times been used to segregate and generate prejudice in relation to bilinguals and/or immigrants, since their performance in cognitive tasks (sometimes measured in their non-proficient L2) was taken as an indicative of their performance in IQ scales.

Also concerned with social issues, the study developed by Morton and Harper (2007) emphasizes the need of observing bilinguals' ethnicity and socioeconomic status when analyzing data. These authors adapted the study developed by Byalistok and colleagues (2005), which has compared monolingual and bilingual children's performance on the Simon task, and concluded that bilinguals show an advantage in decision making due to their better performance in tasks exploring executive functions. Morton and Harper (2007) grouped bilingual and monolingual children of identical ethnic and socioeconomic backgrounds to administer the Simon task. They report an identical performance in the comparison between bilingual and monolingual children; however, there was an advantage for children from higher socioeconomic families in the comparison to the ones coming from lower socioeconomic conditions. As a conclusion, they suggest that the observance of ethnic and socioeconomic differences may attenuate bilinguals' advantage in cognitive control.

Neuroimaging studies have focused on several individual factors related to language acquisition and exposure on the bilingual's language circuitry. Thus, the neurobehavioral literature reports on the impact of age and mode of L2 acquisition (e.g. Giussani et al, 2007; Hull & Vaid, 2007), general proficiency level in L2 (e.g. Muñoz & Marquardt, 2008), as well as proficiency across language processing levels in particular (i.e., speaking, writing, reading and oral comprehension), effective use of the L2, and motivational factors linked to L2 acquisition and use (e.g. Hellermann & Vergun, 2007). All of them are known to have an impact on the network underlying bilingual language processing, and thus may interact with issues related to experimental conditions and analyses.

The next section discusses neuroimaging data on the impact of individual factors on language processing in a non-brain-damaged bilingual population. These data provide evidence on the organization of the bilingual brain, shedding some light on the neurofunctional bases of the dynamics of language processing in bilinguals.

2 FACTORS DETERMINING LANGUAGE ORGANIZATION IN THE BILINGUAL BRAIN: NEUROIMAGING AND NEUROPSYCHOLINGUISTIC EVIDENCE

As already stated, neuroimaging evidence brought by studies which investigated language processing in healthy and brain-damaged participants has shown that language organization in the bilingual brain is influenced by several factors (for a review, see Kotik-Friedgut, 2001; Paradis, 2004; Perani & Abutalebi, 2005). Some of the most relevant factors will be discussed below.

2.1 Age and mode of acquisition

Age and mode of acquisition are very closely related (Kotik-Friedgut, 2001), since early L2 learning generally occurs within a natural environment, and in an informal manner, whereas L2 learning after infancy generally relies upon formal learning methods, typical in academic settings.

Mode of L2 acquisition has been recently associated with different memory systems. Thus, researchers have aimed to analyze the extent to what a more or less incidental way of L2 acquisition may have an impact on the contribution of implicit and explicit memory processing. According to Paradis (2000, 2004), when L2 and L1 are acquired simultaneously by mere exposure and with no need of conscious rule learning, L2 learning will dependent upon implicit

memory processing. On the other hand, late L2 acquisition, in puberty or adulthood, and in an academic setting will depend upon explicit, declarative memory resources. This hypothesis has been challenged by researchers such as McClelland, McNaughton and O'Reilly (1995) and Ullman (2004), whose studies have suggested that L2 use and practice may allow the interaction between these two memory systems, in such a way that conscious and explicit learning may turn into implicit knowledge and automatic use. Future studies, including cross-sectional and longitudinal designs, should examine the role of memory systems in the process of L2 learning. From a neurobiological perspective, there is no converging evidence on the impact of age of acquisition on the neural substrate of bilingualism. For instance, studies at the single-word level, using word completion (Chee, Tan, & Thiel, 1999), semantic judgment (Chee, Hon, Lee, & Soon, 2001), naming (Hernandez, Martinez, & Kohnert, 2000), and noun generation (Briellmann et al., 2004) tasks, have reported overlapping activations for L1 and L2, whatever the age of acquisition. Conversely, studies developed by Kim and colleagues (1997) and Wartenburger and colleagues (2003) report an impact of age of L2 acquisition on the neural substrate for L2 processing. For instance, Wartenburger and colleagues (2003) examined early and late bilinguals' with a syntactic and semantic judgment task; the authors report that late bilinguals show more extended activations in Broca's area, the inferior frontal gyrus (BA44/6) and the right hemisphere homologous region than early bilinguals in the syntactic task, whereas no difference in the activation patterns was observed across groups in the semantic judgment task. Thus, the authors suggest that late L2 acquisition will have an impact on the neural substrate of morpho-syntax but not on the circuitry sustaining semantic processing.

2.2 Proficiency level

A crucial factor to determine L2 distribution and functioning in the bilingual brain is the proficiency level attained in the second language. Research has shown that, in early L2 acquisition stages, para-hipocampal and right hemisphere regions are activated for L2 processing (Paradis, 1997, 2004), possibly to compensate for a lack of implicit L2 knowledge. Several studies have reported wider and more distributed activations in the right hemisphere, particularly in frontal areas, in participants with lower levels of proficiency in the second language (Dehaene et al, 1997; Perani et al, 1996); conversely, highly-proficient bilinguals (Perani et al., 1998) have shown an overlap of L1 and L2 networks in the left hemisphere. In line with the claim that L2 proficiency level determines bilinguals' languages networks, the review developed by Abutalebi and Green (2007) reports higher L2 related activations with low-proficiency participants, not only in regions traditionally involved in L1 processing, but also in regions responsible for the 'cognitive control', such as the prefrontal cortex (BA 9, 46, 47), the anterior cingulate cortex, and the inferior parietal cortex. According to the authors, these activation patterns reflect monitoring processes aiming at inhibiting incorrect responses, and filtering out of unnecessary information available in the environment. Accordingly, Petrides (1998) emphasizes the role of the left prefrontal cortex in sustaining working memory and executive processing, specifically, with regards to the selection and development of adequate strategies for solving complex tasks.

Finally, an important aspect to consider when investigating the impact of proficiency in the bilingual language architecture is the fact that bilinguals may not be equally proficient across language abilities (i.e. reading, writing, speaking and oral comprehension). This variability may result from varying levels of exposure and use of each one of the abilities in daily routine, as well as from the individuals' motivation to improve one or other ability in especial. Therefore, in order to assure homogeneity of the experimental sample, an accurate assessment of the research participant's abilities specifically in the area to be tested cannot be neglected.

2.3 Language exposure and use

The issue of proficiency is closely related to that of L2 use. An assessment of the effective use of L2 and of daily exposure to it should be a fundamental concern (Abutalebi, Cappa & Perani, 2001; Byalistok et al., 2005).

The frequency of the use of a language in daily situations (at home and/or in an academic or professional environment) is directly related to the automaticity obtained, which, in its turn, is linked to the ability in producing and understanding messages in the L2. For example, the L2 structures and vocabulary which are frequently accessed are more easily processed than those rarely utilized (Green, 1998). In other words, a language and/or its components remain with a high threshold if not frequently accessed and, in this way, L2 retrieval and production processes may become a more effortful task.

Finally, exposure to the second language through formal instruction, which is the case of bilinguals who attend academic courses in the L2, needs to be considered. This observance is essential since it may

influence proficiency, in special in specific language abilities developed in formal educational settings, such as writing and reading abilities.

2.4 The age of the L2 user: aging factor

Studies on the neurofunctional organization of brain circuitry for cognitive processing in aging have registered patterns of brain activation which differ from those of young adults when executing the same tasks. These divergent patterns have generated the emergence of several theories which have aimed to explain these shifts in general brain circuitry. Some of these patterns of neurofunctional changes have been described as the following: 1) a higher involvement of frontal areas, possibly due the fact that frontal regions seem to be the first areas affected by age-related deterioration processes (Tisserand, 2002); 2) a posterior-anterior shift in aging (PASA theory), which postulates that with aging there is a migration from posterior areas, including parietal and occipital regions, to frontal areas (Davis et al., 2007), and 3) implies a de-differentiation process, by which tasks previously developed mainly by one brain region are now processed by different brain regions. Further, this shift has been specifically observed with those elderly who keep high levels of performance. These observations have given raise the hemispheric asymmetry reduction in older adults model, or HAROLD Model (Cabeza, 2002).

However, the previously discussed evidence was obtained with monolinguals. The impact of age related changes in brain architecture with bilingual populations is a research field to be explored. Further, the impact of age of L2 acquisition and proficiency level in brain rewiring during aging should also be addressed. Very few studies have investigated the neurobiological and neurofunctional bases of elderly bilinguals' language processing so far. The most recent investigations focus on behavioral data. For example, Byalistok and Craik (2007) and Byalistok, Craik and Ryan (2006) have shown that bilingualism has a crucial effect on cognitive processing, mainly when considering executive functions. Specifically, the authors report a bilingual advantage on tasks that require executive control; this advantage is observed across age-windows but is particularly prominent in the elderly. Moreover, Byalistok, Craik and Freedman (2007) report a four-year delay in the appearance of the first signs in a group of bilinguals presenting Alzheimer's disease, in comparison to monolingual Alzheimer's patients. These data are in accordance with the hypothesis of the establishment of a greater number of connections in the bilinguals' brain (Giussani et al., 2007), and suggest that bilinguals could have access to a cognitive reserve which could compensate for the early signs of healthy and unhealthy aging.

CONCLUSIONS

The study of language processing in healthy and brain-damaged bilinguals is a rich arena. In the lasts decades, the use of neuroimaging techniques has opened a new window onto the neurofunctional perspective of this issue. So far, several studies provide data on the impact of individual factors on language organization in the bilingual brain. Still, much research is required before any consistent theory on the foundations of bilingualism can be proposed. The lack of methodological convergence regarding experimental tasks, design or sample's characteristics has made it hard to draw conclusions and postulate theoretical explanations. Further, thanks to the advent of neuroimaging techniques, researchers have recently focused on the neurofunctional organization of languages in the brain, and its relation with brain structures sustaining memory, atencional and executive functional aspects; still, there is much work to be done on this domain.

Hence, the fundamental question on whether the two or more languages used by bilinguals share or not the same neural substrate is still unsolved. Future studies should take into account the influence of individual factors, as well as the interaction between language(s) and other cognitive functions in the organization of the bilingual brain.

A better understanding of the bilingual brain architecture and functioning will contribute to elaborating theoretical perspectives on the bilingual brain. These will in turn inform neuropsychology and rehabilitation sciences on the specificities of healthy and impaired bilingual language processing, improving assessment and training methods especially designed to this population.

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Recebido em: jan./2008. Aceito em: mar./2008.

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