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·Review·

Neuroimaging studies of bilingual expressive language representation in the brain: potential applications for magnetoencephalography

Elizabeth W. Pang[1,2,3]

[1]*Division of Neurology, Hospital for Sick Children,* [2]*Neurosciences and Mental Health, Sick Kids Research Institute,* [3]*Department of Paediatrics, University of Toronto, Toronto, Ontario M5G 1x8, Canada*

Abstract: Bilingualism is the ability to use two or more languages with equal or near equal fluency. How the brain, often seamlessly, selects, controls, and switches between languages is an enigma. Neuroimaging studies offer the unique opportunity to probe the mechanisms underlying bilingual brain function. Non-invasive methods, in particular, functional MRI (fMRI) and event-related potentials (ERPs), have allowed examination in healthy control populations. Whole-head magnetoencephalography (MEG), a relatively new addition to the cadre of neuroimaging tools, offers a combination of the high spatial resolution of fMRI with the high temporal resolution of ERPs. Thus far, MEG has been applied to the studies of bilingual receptive language, or bilingual language comprehension. MEG has not yet been applied to the study of bilingual language production as such studies have faced more challenges (see Salmelin, 2007 for a review), and these have only recently been addressed. Here, we review the literature on MEG expressive language studies and point out a direction for the application of MEG to the study of bilingual language production.

Keywords: magnetoencephalography; bilingualism; expressive language

1 Review of the neuroimaging literature

Bilingualism is defined as the use of two (or more) languages with equal or near equal fluency[1]. Available estimates suggest that two-thirds of the world's children grow up in bilingual environments[2] and that the use of two or more languages characterizes the majority of the world's population. Over the last decade, greater access to the internet, increased ease of travel and migration, and higher levels of global trade and commercial activity have continued to facilitate the sharing of culture, ideas, economics, and ultimately, language. Moving in parallel with this phenomenon, there is a growing interest in understanding the neurobiology of the bilingual brain.

Neuroimaging research offers a unique opportunity to examine the neural underpinnings of the bilingual brain. Clinical studies[3-6] which reported unusual patterns of aphasias, usually due to neuropathology, in multilingual individuals were the first to raise the issue of brain differences between mono- and multi-lingual persons. Invasive studies[7-9] involving direct cortical recordings and stimulation emphasized the need to look at multiple language use. Examination of bilingualism in healthy populations was not possible until the advent of non-invasive functional neuroimaging techniques.

To gain an overview of the functional neuroimaging techniques that have been used to study bilingual language representation in the brain, it is important first to under-

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Corresponding author: Elizabeth W. Pang
Tel: +1-416-8136548; Fax: +1-416-8136334
E-mail: elizabeth.pang@sickkids.ca
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stand language representation in the brain. Human language is a complex phenomenon that requires precise integration of numerous brain regions, and several models of language based on neuroimaging data exist[10]. While these frameworks are helpful, for this review, the most common neuropsychological model will be used. The classic Wernicke-Geschwind model of language organization[11] suggests that expressive language is subsumed in Broca's area[12] located at the pars triangularis and operculum of the left inferior frontal gyrus. Receptive language is located in Wernicke's area[13] at the left temporo-parietal junction. These areas have complex, reciprocal connections between primary sensory, secondary sensory, and association areas which have been outlined in more complex models[14-16]. Notwithstanding the limitations inherent in a simplified model, the Wernicke-Geschwind structure is helpful for organizing the neuroimaging literature.

Electrophysiological, or event-related potential (ERP), studies have focused primarily on receptive language paradigms. The use of listening or/and silent reading paradigms allows researchers to avoid muscle contamination artifacts due to mouth movements during language production. The excellent temporal resolution, in the order of milliseconds, is useful for examining functional differences in bilingual language reception; however, the poorer spatial resolution of ERPs does not allow them to provide good information regarding differences in neural locations for separate languages. ERP studies, along with functional MRI (fMRI) studies, have been recently reviewed[17,18].

Positron emission tomography (PET) and fMRI studies offer better spatial resolution and have used a combination of paradigms that activates both receptive and expressive language in the same task. One of the first PET studies showed left frontal lobe activation including the inferior frontal gyrus and left pre-motor area for first (L1) and second (L2) languages, regardless of task or language, suggesting that common brain areas are involved in within- and across-language searches[19]. One of the first fMRI studies[20] reported that L2 was spatially separated from L1 if the subject learned their second language later in life, whereas "early" bilinguals showed both languages in spatially common frontal cortical areas; however, subjects' language proficiencies were not controlled and language comprehension was not directly tested, thus, interpretation of these results is difficult. Furthermore, late-acquisition subjects showed more variability in the neural areas activated[21]. An event-related fMRI comparison of L1 and L2 picture-naming showed differential activations in bilateral anterior cingulate cortices, left inferior, left middle, and right dorsal frontal gyri and left pre-central gyrus[22]. However, both PET and fMRI results represent only the strongest summed activations over time and may not capture the subtleties that are involved in L2 use. A paper reporting the results of a meta-analysis of hemodynamic studies of bilingualism points to the huge variability in the literature, and suggests that this is primarily due to differences in experimental parameters; however, the author concludes that despite these limitations, there are differences in the activation patterns between L1 and L2 that likely are not due to coincidence although the factors of L2 onset, proficiency and exposure need to be controlled and consistent between subjects[23]. More recently, fMRI work on expressive language and bilingualism has turned to examine bilingual language control[24,25], particularly for language switching[26,27], language selection and inhibition[28].

2 MEG studies of bilingual receptive language

A promising modality for the study of bilingual language representation is magnetoencephalography (MEG). MEG measures the tiny magnetic fields induced by the current flow resulting from synchronized neuronal firing. With appropriate source localization techniques, this technology offers spatial resolution approaching that of fMRI; with increasingly higher sampling rates, the temporal resolution of MEG is in the order of a millisecond or less. This high spatial and temporal resolution makes it a good candidate for examining the spatiotemporal dynamics of language[29], and L1 and L2 representation in the brain.

There is an extensive literature on MEG studies of bilingual receptive language processing and this is reviewed by Schmidt and Roberts[30]. Bilingual receptive language has been examined using a number of neurophysiological components including the M100, the M400, and the mismatch field (MMF). The M100 is an early component evoked at ~100 ms after auditory stimulus onset. Its amplitude and latency are known to vary with the spectral and temporal attributes of the stimulus and it is thought to be involved in auditory stimulus detection and feature extraction[31]. The M100 is reliably elicited by tones, speech sounds and words, and its neuronal source is located on the planum temporal[32]. The M400[33] is the magnetic correlate of the N400[34] and is involved in processing higher-order aspects of language such as semantic difficulty and depth of semantic processing. Its neuronal generators have been localized to the left hemisphere temporal and frontal language areas[35,36]. The MMF is the most robust of the auditory cortical responses. It does not require direct attention and can be reliably evoked in infants and young children[37]. It represents the brain's ability to detect an auditory difference in tonal or linguistic stimuli[38,39]. While all of these components have been used in the study of bilingual processing in the brain, the most frequently used in the study of receptive language is the MMF. Studies examining bilingual receptive language have looked at bilingual word processing, word reading, word listening, and sentence grammar violations. Again, these studies have been well reviewed[30].

There have been only two recent studies using MEG to examine bilingual receptive language. The first[40] used a visual semantic size judgment task in the MEG. Subjects were bilingual adults who acquired their second language early in life. The findings showed that L1 and L2 activated similar left hemisphere visual and ventral frontotemporal regions associated with semantic processing; however, L2 activations were delayed and more bilateral in homologous areas, but the bilateral activity disappeared with greater fluency. Following up this study, the same group[41] used the semantic judgment task with a priming effect and reported that L1 and L2 processing employed the same classic brain areas used by monolinguals; however, when subjects were less proficient in L2, they recruited additional areas, primarily in homologous right hemisphere regions.

3 Potential application of MEG to studies of bilingual expressive language

Expressive language tasks in the MEG are less common because the artifacts and trial-by-trial variability of speech production have been problematic for the small neuromagnetic signals[42]. Some groups have found creative approaches to solve these problems, for example, by using a delayed-responding paradigm[43]. Other groups have developed source localization techniques, such as beamforming[44,45], to separate out the artifact source and identify brain areas involved in expressive language[46-48]. These novel MEG expressive language tasks have not yet been applied to the question of bilingual language representation in the brain.

Here, we report a preliminary study (unpublished data) involving ten healthy young adults (three male, seven female) with a mean age of 23.5 ± 3.9 years. All subjects were right-handed and had a mean age of L2 acquisition of 5.7 years. Subjects completed detailed language questionnaires and self-reported an L2 spoken fluency of 5.2 on a 7-point Likert Scale where 1 represented basic fluency and 7 represented perfect fluency. Self-reported L2 comprehension was higher, with a rating of 5.7 out of 7. Subjects also used a 10-point scale (+5 represented L1-dominance, –5 represented L2-dominance, and 0 represented equal balance) to report the balance of the L1/L2 usage and L1/L2 ability. For the former, the mean score was +1.0, indicating a slight dominance of L1 use; while the latter showed a mean score of +2.1, indicating a slightly greater dominance for L1 ability. Overall, subjects were fairly proficient in their second language.

Subjects completed a covert verb generation task to picture stimuli[48,49], in both their first and second languages, while lying in the MEG. After testing in the MEG, subjects performed the same task with covert responses, outside the scanner, to allow validation of their performance. Data were divided into epochs from –200 to +700 ms and separated into three bands: 5–15 Hz, 15–25 Hz, and 25–50 Hz. The data within each band were analyzed using differential beamforming[44,45,50,51] in consecutive, overlapping 150-

ms windows compared to a 150-ms pre-stimulus baseline. The pre-stimulus window was fixed at –200 to –50 ms. The active analysis windows were: +50 to 200, 150 to 300, 250 to 400, 350 to 500, 450 to 600, and 550 to 700 ms. We have previously used this approach to localize receptive language areas in a cohort of young children[52]. The region of interest included the whole cerebral cortex with 5-mm voxel resolution. Areas of event-related desynchrony were submitted to a bootstrap statistical procedure and only results passing a threshold of $P < 0.01$ were reported.

In the lowest band of 5–15 Hz, L1 use showed early and sustained (50 to 450 ms) left inferior frontal gyrus activation; this same activation was seen much later (starting at 450 ms) in the homologous right inferior frontal gyrus for L2. Interestingly, for L2, the inferior frontal gyrus response was preceded by an early and sustained activation in the right insula (Brodmann area 13), a known language control area. In the beta band (15–25 Hz), as expected, activity was seen in the motor areas. For both L1 and L2, activation started in the mouth motor area and proceeded superiorly to the hand motor area. However, these areas demonstrated a lag for L2, and for L2, were preceded by activation in the right anterior cingulate cortex (Brodmann area 32), another known language control area. In the gamma band (25–50 Hz), for L1, activity was seen in the left superior frontal gyrus and left insula, while for L2, activation was in bilateral frontopolar regions. These regions are part of the dorsolateral prefrontal cortex and are known to be involved in cognitive processes, including executive control, memory, attention, inhibition and planning.

The most striking findings from this study are that of early and sustained involvement of the insula and cingulate cortex with L2 use. There are several ways to interpret these results. One fMRI study suggested that the insula is involved in switching between L1 and L2; specifically, the insular activation demonstrates a priming effect for activating the appropriate language[53]. However, a recent MEG study[41] suggested that insular activation is related to lower proficiency on L2 and not directly to L2 use. Either of these interpretations would fit our data; however, our finding that this insular activation engaged immediately is new. Cingulate cortex activation has been seen in fMRI and interpreted as a sub-process inhibiting the inappropriate language[53]; however, other models of bilingual language control identify the anterior cingulate cortex as being important in conflict-monitoring and error-detection[54,55]. Our data fit better with the latter interpretation, as our subjects self-reported a slightly lower fluency in their L2; thus, it would be consistent that this lower proficiency would result in a need for greater error-monitoring.

Our data also demonstrated greater involvement of homologous areas in the right hemisphere; specifically, we found left dorsolateral pre-frontal cortex activation for L1, and bilateral homologous areas for L2 use. This is consistent with the MEG study of bilingual receptive language which reported additional recruitment of right hemisphere homologous areas for L2 compared to L1 use[40]. This is also consistent with an fMRI study that suggested that the anterior cingulate is connected to the dorsolateral frontal cortices, and that these areas are involved in language control, specifically response-selection and inhibition of interference from the inappropriate language[54,55]. Our finding of a very early cingulate response in the L2 condition supports the idea that the cingulate signals the possibility of response conflicts to the dorsolateral prefrontal cortex, thus priming these control regions to respond appropriately.

To summarize, our results demonstrated that L1 and L2 activate similar brain regions; however, L2 processes were delayed, due to the early involvement of control processes that activated appropriate, and inhibited inappropriate, language selection. Furthermore, we concur with current thinking that L2 processing requires more bilateral resources than the primarily left-lateralized L1 processes.

4 Summary

In this example of a preliminary experiment where MEG was used to acquire data in a bilingual expressive language task, we were able to obtain timing information, in addition to the spatial localizations of neuronal areas involved in first and second language use and control. These data allowed us to examine the relative patterns of activations between different brain regions in bilingualism.

Clearly, there is great value to adding MEG to the cadre of neuroimaging tools.

Furthermore, these preliminary MEG data have implications for understanding more recently proposed, complex models of language. While the classic Wernicke-Geschwind model is helpful for designing experiments, it is not adequate to interpret neuroimaging findings which can capture the more complex patterns of neural activation involved in L1 and L2 use. Recent developments in models of bilingual language, based on fMRI[40,54,56], identify additional regions involved in second language control. The results in this study complement what is seen with fMRI, and fine-tunes the information offered by ERPs. With increasing interest in bilingualism and the impact of learning multiple languages, there are ample questions and topics of research using MEG.

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