

Neuroimaging of Language: The Contribution of fMRI

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INTRODUCTION

Since the start of contemporary neuroimaging techniques during the late 20th century, analysis of the brain's organization of language has represented one of the major topics of research [1]. Different types of neuroimaging procedures have been developed to analyze both morphology and brain activity. Although functional Magnetic Resonance Imaging (**fMRI**) represents the main neuroimaging research and clinical technique, other procedures including Positron Emission Tomography (**PET**), Magneto-Encephalography (**MEG**), Event Related Potentials (**ERP**), Diffusion Tensor Imaging/Tractography DTI-Tractography, and Transcranial Magnetic Stimulation, are also frequently used [2]. However, because of its versatility and lack of invasiveness fMRI has become particularly popular during the last decades and dozens of research studies are continuously published worldwide [3]. Furthermore, fMRI has opened new research approaches, in particular the study of resting-state-fMRI (**rs-fMRI**) [4]. Because of these reasons, most of the content of this paper will be devoted to fMRI.

In this chapter, neuroimaging studies of language understanding as well as language production will be presented. The potential language-coordinating role played by the insula will be briefly mentioned. In addition, studies regarding brain activation during reading and writing will be later reviewed. Some general conclusions are finally presented.

LANGUAGE UNDERSTANDING

A number of studies have analyzed language recognition and understanding usually using fMRI and, in a lesser degree, PET [5]. It has become clear that the processing of speech correlates with significant activation in the primary auditory area (Brodmann area –BA--41 and BA42) and adjacent cortical zones [6,7]. Neuroimaging research results have demonstrated that the initial stage of speech perception takes place in the posterior part of the planum temporale. It is observed that this area becomes activated when sequences of syllables are heard [8], and evidently is involved in the phonological recognition of the language. Considering that the planum temporale is also activated when reversed speech is presented, it has been suggested that this auditory processing is automatic and not necessarily related to prior memories [9]. That is, it involves the recognition of sound units (phonemes), not the recognition of meaningful learned information (morphemes or words). Therefore, the primary auditory area is involved in the recognition of sublexical units (phonemes, syllables) as an initial step in language understanding. Noteworthy, in so-called Indo-European languages such as English and Spanish, phonemes are distinguished according to three articulatory features: manner of articulation, place of articulation, and voicing. Interestingly, specific neural representations corresponding to the categorical features of manner of articulation, place of articulation and voicing have been reported in the superior temporal lobe [10]. Figure 1 presents a typical example of the involvement of the primary auditory area when auditory speech is processed.

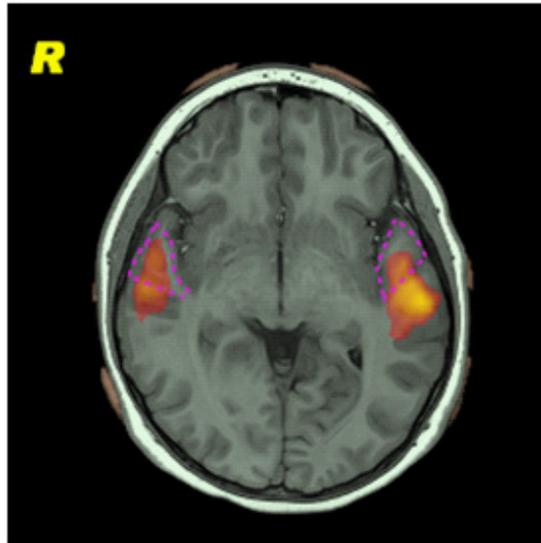


Figure 1: Language fMRI in a 7-year-old right-handed boy. Activation from a speech perception task. Transversal cut in radiological orientation (right on the left) at the level of the planum temporale and Heschl's gyrus (primary auditory cortex). Primary auditory areas have been outlined with purple dashed lines. Notice the bilateral involvement and the greater extent and intensity on the left side, particularly toward the planum temporale (posterior adjacent to the primary auditory areas). Image from the Radiology Department of Nicklaus Children's Hospital.

Since Wernicke [11], the superior temporal gyrus, corresponding to BA22, has been considered as the most crucial area in generally language comprehension; words understanding, in particular. In the left hemisphere, BA22 is frequently referred as "Wernicke's area". Using neuroimaging studies, it has been observed that BA22 is involved in a diversity of language related tasks, including not only auditory language processing (e.g., [12,13]), but also in semantic processing [14,15], selective attention to speech [16], repeating words [17], processing complex sounds [18] and lexico-semantic access to melodic representations [19]. Ultimately, Wernicke's area pathology results in so-called Wernicke aphasia, characterized by language understanding difficulties, verbal memory impairments, word-finding defects, and language output errors (paraphasias) [20,21].

In addition to BA22, BA21(middle temporal gyrus) often participates in language recognition and should in consequence also be included in Wernicke's area. Recent neuroimaging studies have demonstrated that BA22 activates in a diversity of linguistic conditions, including: selective processing of speech [22], semantic processing [14], word generation [23], sentence generation [24], and complex sound processing [18]. It can be consequently conjectured that while BA41 and BA42 participate in sublexical recognition (i.e., phonemes and syllables), BA22 and BA21 are involved in lexical recognition (i.e., recognizing morphemes and words).

Departing from several fMRI meta-analytic studies on Brodmann areas involved in language understanding, Ardila, Bernal and Rosselli [25] have proposed that the “core Wernicke’s area” corresponds to BA41, BA42, BA22 and BA21. This core Wernicke’s area is involved in the phonological and lexical recognition of words.

According to contemporary neuroimaging studies, other brain areas beyond BA22 and BA 21 also participate in auditory language recognition. These additional areas include BA20 (inferior temporal gyrus, and anterior part of the fusiform gyrus) [26], BA37 (inferior temporal gyrus, fusiform gyrus), BA38 (temporal pole) [27], BA39 (angular gyrus) [28-32] and BA40 (supramarginal gyrus) [15,33]. These areas are involved in word associations and can be regarded as kind of “extended Wernicke’s area”.

Understanding language beyond individual words, but rather in a complex context, requires the participation of multiple brain areas. Ferstl, Neumann, Bogler, and Von Cramon [34] conducted a meta-analysis of 23 neuroimaging studies on text comprehension, directed to confirm the extension of the brain network involved in processing language in context. It was found that independent of the baseline, the anterior temporal lobes were bilaterally active. In addition, processing coherent compared to incoherent text engaged the left dorso-medial prefrontal cortex and the posterior cingulate cortex. Furthermore, right hemisphere activations were seen most notably in the analysis of contrasts testing specific sub-processes, such as metaphor comprehension. These results suggest that when language comprehension is processed in a context, it is associated with an extensive brain activation network, involving not only the left, but also the right hemisphere. Nonetheless, text comprehension supposes diverse abilities (for example, abstraction, metaphor understanding, etc.), beyond the purely auditory language understanding of individual words.

LANGUAGE PRODUCTION

Language production has been classically related with the Broca’s area activity, corresponding to BA44 and BA45. Using neuroimaging studies, BA44 has demonstrated to be involved in a diversity of verbal functions, including verbal fluency, phonological processing, grammar processing, attention in speech, and sentence comprehension [21,22,35,36]. In addition to these language functions, BA44 has been found active in many other non-verbal functions, such as processing sequential sounds, working memory, mirror neuron systems, motor inhibition, object manipulation, and music enjoyment [22,35].

Neuroimaging studies have also extensively supported the participation of BA45 in language production. At least in the following verbal functions, BA45 has been found active: Grammatical processing [36], phonological processing [37], verbal fluency [38], lexical search [39], selective attention to speech [40], reasoning processes [41], and semantic memory retrieval [42].

Bernal, Ardila and Rosselli [43] developed a meta-analytic study for the BA44 brain connections based in fMRI activation. Fifty-seven papers that included 883 subjects in 84 experiments were

analyzed. Main clusters of activation were located in the frontal operculum, left posterior temporal region, supplementary motor area, and the parietal lobe. Less common clusters were seen in the sub-cortical structures including the left thalamus, left putamen, secondary visual areas, and the right cerebellum (Figure 2).

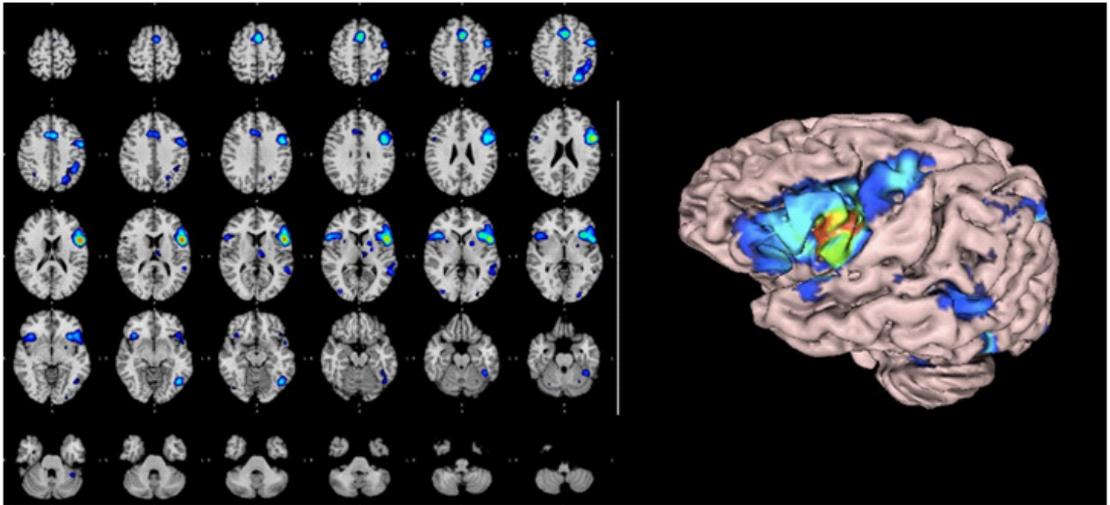


Figure 2: Functional connectivity map of BA44 by Meta-analytic connectivity modeling. Left side of the panel: transversal descending cuts of the brain MRI template. Left hemisphere appears on the right side (Radiological convention). Clusters of activation are color coded for statistical significance from dark blue (lowest) to red (highest). Main clusters of activation involve the seeding area (left BA44), BA45, and Brodmann’s adjacent areas: 9, 6, 13 (anterior insula) and 46, all in the left side. In the midline there is a cluster involving BA32 (pre-SMA). Posteriorly, the largest clusters include BA7, BA39, BA40, BA37 and BA22. Subcortical structures are also activated: left thalamus and left putamen. The left cerebellum shows activation as well. Right side of the panel: 3D volumetric rendition of the brain showing activation on the left hemisphere surface. Red color zone identifies BA44. Deep and midline activations are not shown (Taken from Bernal, Ardila and Rosselli, 2015 [31]).

Departing from seven neuroimaging meta-analytic studies, Ardila, Bernal and Rosselli [26] have suggested that BA44, BA45, BA47 and mesial BA6 participate in kind of “frontal language production system” (or “Broca’s system”). This Broca’s system extends subcortically to the lenticular nucleus and the thalamus.

The Insula: Coordinating Language Understanding and Language Production

Contemporary neuroimaging technique studies support the insula’s direct involvement in linguistic processes. Activation of the insula has been demonstrated in a diversity of verbal tests, including word generation [44-46]), naming [47,48], and phonological discrimination [49,50]. The insula has also been related to auditory processing [51]. It can therefore be concluded that contemporary neuroimaging studies support the assumption of a significant participation of the insula in language.

Moreover, Ardila, Bernal and Rosselli [52] developed a meta-analysis of fMRI studies aimed to pinpoint the participation of insula in language; 26 papers corresponding to 39 paradigms, where 522 participants were selected. Thirteen different activation clusters were found; insula connections included not only areas involved in language production (such as the Broca's area) and language understanding (such as the Wernicke's area), but also areas involved in language repetition (such as the supramarginal gyrus) and other linguistic functions, such as BA9 in the left prefrontal lobe (involved in complex language processes) and BA37 (involved in lexico-semantic associations). The authors concluded that the insula represents a core area in language processing, as it had been suggested during the 19th century.

READING AND WRITING

Since the initial neuroimaging studies, it was observed that the left extrastriate visual cortex plays a central role in word recognition [53]. It was found that this area becomes active with the visual presentation of words. Two additional cortical areas involved in reading were further described: the left angular gyrus [54] and the left ventral occipitotemporal cortex [55,56]. The left occipitotemporal area has been considered most crucial and has even been named as 'Visual Word Form Area' (**VWFA**); this particular cortical area is observed to be activated during the visual processing of words not only in English, but also across different languages (e.g. [57-60]). Furthermore, when pseudowords are presented, when letter strings become more word-like activation increases, suggesting that learning to read tune these cortical areas to the combination of letters, that is, words [61,62].

The neural correlates of eye fixation during natural reading has been investigated using fMRI [63-65]. Different experimental tasks were developed: natural reading, natural reading vs scene viewing, normal and non-word text reading. The results showed an association with fixation duration, activation in oculomotor and language areas during text reading; fixation duration during pseudo-reading, on the other hand, showed greater involvement of frontal control regions. In addition, the eye movement control network including the frontal eye field, supplementary eye fields, and intraparietal sulcus, were involved in reading and scene viewing, suggesting that a common control circuit participates in controlling eye movements. Normal reading is associated with activation in a language network that includes the superior temporal gyrus/sulcus, middle temporal gyrus, angular gyrus, inferior frontal gyrus, and middle frontal gyrus.

Using fMRI, Hayashi et al. [66] observed that reading concrete and abstract words results in a different pattern of brain activation. Concrete words elicited significantly more activation than abstract words in the left middle frontal gyrus bilateral superior frontal gyrus, and left fusiform gyrus. The authors proposed that these differences are the result of the visual imageability of concrete and abstract words: Concrete words have higher imageability than abstract words, such that they elicit more visual imagery.

After reviewing the neuroimaging research in reading and writing published during 20 years (1992-2012) Price [5] concluded that an extensive region of the ventral occipitotemporal cortex is involved in skilled reading. Within this region two different segments can be distinguished: (a) posterior areas are involved in visual feature extraction, whereas (b) more anterior areas participate in lexical and semantic processing of the words.

CONCLUSION

Contemporary neuroimaging studies have significantly advanced our understanding of the brain organization of language. It has been observed that the left temporal lobe participates in phoneme recognition and lexical understanding. Language production is controlled by a large brain system including BA44, BA45, BA46, BA47, mesial BA6 and extending subcortically. Furthermore, the insula seemingly plays a coordinating role between both language understanding and language production systems. Ultimately, neuroimaging techniques have significantly contributed to the understanding of brain organization when reading and writing; it has been found that some specific brain areas support the ability to read, including the ventral occipitotemporal cortex, the left extrastriate visual, and the angular gyrus.

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