Review Article

Application of Functional Magnetic Resonance Imaging in Neurolinguistics: A Systematic Review

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1. Introduction

As an interdisciplinary field, neurolinguistics uses theories and methods from psychology, cognitive neuroscience, and linguistics to clarify the underpinnings of language formation and processing in the brain.

To achieve this purpose, linguistics utilizes different methods such as clinical observation, corpus analysis, psychological experiments, and importantly, neuroimaging methods such as Positron Emission Tomography (PET) scan, Electroencephalography (EEG), Magnetoencephalography (MEG), and functional Magnetic Resonance Imaging (fMRI). Choosing the proper method brings about a debate on the advantages and disadvantages of each technique. Considering the abstract and complicated nature of language processing, the researcher should decide whether to give priority to the temporal resolution or spatial resolution of the language-related tasks. Optimistically, fMRI offers a high degree of temporal resolution along with an acceptable spatial resolution enough to identify interregional functional connectivity that makes language formation possible [1].

1.1. The Advantages and Disadvantages of fMRI in Linguistic Research

According to Stemmer and Whitaker (2008), fMRI offers three important advantages when used in linguistic research. These include a better spatial resolution, its temporal resolution, and the non-invasive nature of the study, enabling several scans to be performed on a single subject and in a non-medical environment [2].

The noise in the MRI tube, which is about 93–98 db in a 1.5 T scanner and more in higher Tesla scanners, is a significant technical disadvantage of fMRI. Subjects need to wear protective ear-phones during experiments, making it hard to implement experiments with auditory stimuli or data. The fMRI's BOLD signal is generated based on fluctuations in blood oxygen level as a result of increased or decreased neuronal activity in distinct parts of the brain. Nonetheless, despite the real-time and dynamic nature of the BOLD signal, which prioritizes it over glucose uptake rate identified through PET and cerebral blood flow rate, fMRI is not the ideal method in researches on language production or perception where the processing speed does not exceed 100 milliseconds. In addition, fMRI necessitates subjects with a history of seizures, those with certain metal implants, those with cardiac pacemakers, etc. to be excluded from the experiment, which might impose potential selection bias

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in the study groups. Finally, compared to the simple equipment needed for EEG recordings or magnetoencephalography, fMRI installations are huge and costly [2].

2. Materials and Methods

We performed a comprehensive search on ProQuest and Scopus search engines using keywords: "functional MRI", "fMRI", and "linguistics", "phonetics", "semantics", and their synonyms, yielding to a total of 343 articles. We then extracted original research papers that used fMRI in the study of neural bases of language in human participants. Two authors independently screened the research papers and relevant articles were extracted based on title and abstract. Finally, we included 23 articles based on full-text review which conducted original research on different aspects of language processing using fMRI. Studies regarding applied linguistics such as language acquisition, second language learning, and bilingualism, as well as studies using subjects with any neuropsychological disorders, were excluded. Included studies were categorized according to the language areas they investigated, including phonetics and phonological processing; semantics; and syntax. This paper gives a comprehensive review of the recent linguistic research carried out with the help of fMRI and it tries to summarize the findings of such research.

3. Results

3.1.Phonetics and Phonological Processing

Language comprehension is the process of perception of the acoustic information and necessitates the activation of the so-called "core language system" [3, 4]. The core language system is a resting state of the functional network of the brain which deals with all aspects of language perception, including phonological, syntactic, and semantic processing [5]. By definition, phonetics and phonology deal with sounds of speech and language. Phonetics is about the physical aspect of sound production and phonology pertains to the abstract aspects of sound such as the realization of words and phrases, stress and accentuation or intonation at a suprasegmental level.

The auditory cortex of both hemispheres is responsible for phonological comprehension of language at the first level. All the three regions of the primary auditory cortex, the Heschl's gyrus, the planum polare, and the planum temporale are actively involved in the acoustic-phonological analysis of speech, while the Heschl's gyrus serves more in general auditory functions. It has been suggested that the primary auditory analysis is performed in the Heschl's gyrus, as the Heschl's gyrus has been shown to be activated by almost all types of auditory stimuli. Based on phonological specifications, the output processing of "segmental" sounds will continue in the left hemisphere and the "suprasegmental" sound processing in the right hemisphere [6, 7] These finding are reported in Friederici, 2017 [5].

Functional categorization of different sub-regions within the superior temporal gyrus/sulcus of the left hemisphere into three parts- posterior, middle, and anterior, has been clearly described by Giraud and Price [8]. The bilateral Superior Temporal Sulci (STS) and the Inferior Frontal Cortices (IFC) are shown to be selective for voice, and are sensitive to rapid voice changes and short-term voice stimulus similarity [9]. Similarly, in line with greater phonological working memory charge, the bilateral STS, IFC and the Supplementary Motor Area (SMA) showed neurophysiological responses. In line with this, the activation in the left STS during non-word discrimination correlated with the participants' performance on standard clinical non-word repetition tests [10]. More details about the exact spatial activation of the brain during various sound and language component processing has been provided in a review article in 2012, which is a synthesis of the first 20 years of PET and fMRI studies of heard speech [11].

Importantly, spoken language and reading tasks are shown to demonstrate activation in different parts of the brain [11]. In a scientific report, Rampinini *et al.* [12] focused on functional and spatial segregation within the inferior frontal and superior temporal cortices during listening, articulation imagery, and production of vowels they found that left IFGpTri and left pMTG/STG shared sensitivity to both tones and Italian vowels. Together, these results suggest that phonological working memory is related to the function of cortical structures that canonically underlie speech perception and production.

Table 1. Summary of studies using fMRI in auditory processing and articulating. Figure 1 summarizes areas found in the results of these papers

	Study	Area: results	Target	Content	Subjects
1	Price (2012) (review article) [11]	right superior temporal	frequency spectrum, rhythm intonation	heard speech, spoken language and reading, prosodic processing of speech	healthy adults
2	Andics, *et al.* (2013) [9]	bilateral superior temporal sulcus (STS) /inferior frontal cortex (IFC)	voice-selective cortical regions in maintaining long-term voice knowledge	newly-learned voice categories, Mean-based neural coding of voices	15 Dutch female healthy adults
3	Argyropoulos, G. P. *et al.* (2013) [13]	Putamen and the caudate, the two major inputs to the basal ganglia, Results: the putamen undertakes articulation-related aspects across tasks, while the caudate selectively supports selection processes in sentence generation.	The role of these basal ganglia structures in sentence repetition and generation	Sentence repetition and generation	21right-handed native speakers of English (mean: 25±4.4 years of age; 10 males)
4	Clos, M. *et al.* (2013) [14]	Cytoarchitectonic left area 44 of Broca's : action processes: phonology and overt speech (posterior-dorsal cluster), rhythmic sequencing (posterior-ventral cluster); language and cognition: working memory (anterior-dorsal cluster, detection of meaning (anterior-ventral cluster) , task switching/cognitive control (inferior frontal junction cluster)	Five separate clusters exist within left area 44; whole-brain co-activation pattern	Overt speech, rhythmic sequencing: working memory: detection of meaning: task switching/cognitive control	153 (mean of age 41.1±18.0 years old; 92 males)

5	Belin (2017) [15]	Right anterior temporal lob	Voice patches	Face and voice processing, Norm-based coding	-
6	Meltzera & panamsky (2017) [16]	Temporal and extra-temporal cortices	Voice -sensitivity, or "voice patches	The human voice areas	218; 117
7	Leaver & Rauschecker (2016) [17]	Auditory cortex Functional topography delineates sub regions of human auditory cortex	Nature of topographic organization in human auditory cortex	Spectral frequency(tonotopy): temporal modulation (periodotopy)	13 (8 female; mean of age, 26.5 years old; SD, 3.7 years)
8	Rampinini *et al.* (2017) [12]	Left IFGpTri and left pMTG/STG shared sensitivity to both tones and vowels: patches of cortex in inferior frontal and superior temporal regions retained information to significantly discriminate the seven vowels of the Italian language in each condition	Sub-regions within frontal and temporal speech-related areas; phonological representations during both perception and production	Vowels of the Italian language; listening, imagery and production	15(9 F; mean of age 28.5±4.6 years) Italian monolingual speakers
9	Perrachione *et al.* (2017) [10]	Cerebral Cortex	Phonological Working Memory	Words and Non-words	16

Anterior Broca's area: BA 45, posterior Broca's area: BA 44, left posterior superior temporal gyrus: lpSTG, right inferior precentral sulcus: rIPS, left inferior frontal gyrus: LIFG, inferior portions of the LIFG: BA 47, temporal pole;: TP, anterior superior temporal sulcus: a STS, temporo-parietal junction: TPJ, left inferior frontal cortex: l IFC, left posterior temporal cortex: lpTC, left posterior middle temporal cortices: lPMTC, visual word form area: VWFA, inferior frontal gyrus:IFG, posterior superior temporal sulcus: pSTS, left inferior frontal cortex: BA 45, left middle frontal gyrus: BA 46, left middle frontal gyrus: lMFG, anterior temporal lob: ATL, angular gyrus: AG, superior temporal sulcus:STS, right anterior temporal lobe: raTL left inferior frontal gyrus pars triangularis: lIFGpTri, left posterior middle temporal gyrus: lpMTG/STG superior temporal gyrus: STG

Table 1 includes a summary of research papers using fMRI in auditory processing and articulating. All these studies used auditory stimuli and listening tasks for healthy adults.

3.2.Semantics

Semantics is another core component of linguistics that deals with the meaning of words and sentences, either explicit or implicit. Functional MRI studies have revealed specific regions in the brain that are activated during semantic processing, areas in charge of single word processing and specific regions for sentence processing. As a result, studies focusing on semantic processing are designed to investigate the relations between semantics and syntactic aspects of language forms (Table 2). Research on language semantics can be divided into two parts: first, studies that focus on lexical entry of the encoded information, a process, which, according to the cognitive model of auditory language

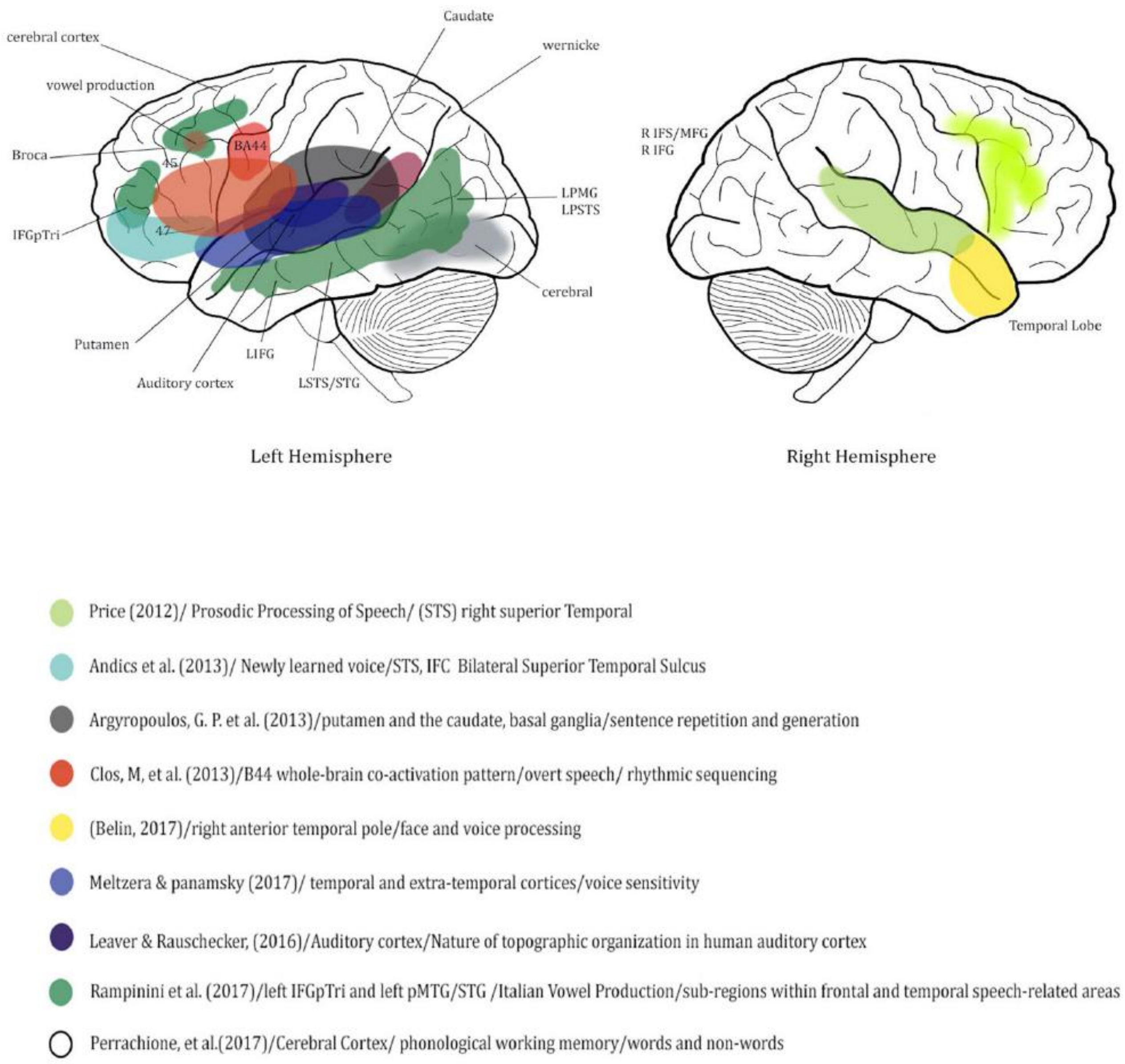

Figure 1. Results of articles using fMRI in auditory processing and articulating

comprehension, is the primary step. The temporal cortex and in particular the temporal gyrus, together with the medial temporal lobe and the hippocampus, are known to be involved in lexical entry. Second, are the studies focusing on sentential semantic aspects of the language, which has to deal with the semantic and the thematic fit between the different argument noun phrases and the verb. Importantly, the anterior temporal cortex and the left anterior temporal lobe are shown to be the primary regions necessary for word comprehension and also conditional for sentence comprehension, where meaningful units are built [11, 18]. The functional role of the anterior temporal lobe within the language network, however, is still under discussion [19].

As mentioned, the lexical entry is found to be the result of a complex interplay between the temporal gyri, together with the medial temporal lobe and the hippocampus, within the temporal lobe. Semantic aspects of the language, in turn, activate more anterior portions of the inferior frontal gyrus, namely BA 47 and the anterior portion of BA 45, particularly when lexical processes are under strategic control [20] or when the sentential semantic context is examined [11]. Indeed, semantic-related activations in the temporal cortex are mainly reported during sentence processing and in the anterior temporal lobe, the posterior superior temporal gyrus [21], and also in the angular gyrus [22, 23]. However, a recent meta-analysis across sentence processing studies suggests involvement of BA 45/47 during the processing of semantic aspects [5, 24].

Other areas of research papers deal with different cognitive properties related to language processing. Takashima *et al.* [25] showed that the medial temporal lobe and in particular the hippocampus play a major role in semantic processing and specifically during the learning of novel words, in line with the role of the medial temporal lobe in memory encoding. Wallentin *et al.* [26] investigated whether lateralized BOLD-fMRI activations in Broca's region, Wernicke's region and the Visual Word Form Area (VWFA) indicate task shift costs and also to what extent these effects are specific to language-related task shifts. This research found out that lateralization for individual tasks was correlated across brain regions, but not across tasks, suggesting that lateralization may not be a unitary phenomenon, but rather varying across participants according to task demands. Patterson and Lambon Ralph [27] conducted a recent large-scale meta-analysis and studied the processing of thematic or combinatorial semantics in a memory system with episodic tasks.

It is undeniable that researches on semantic processing are related to other aspects of language especially syntax and morphology. We have therefore summarized researches related to semantic processing and syntax in the same table (Table 2).

3.3.Syntax

Last but not least, we focus on papers considering syntactic processing. Syntax is defined as principles and processes that govern the structure of well-formed sentences in a language. Words are the building blocks of language comprehension and the sequencing of words makes a sentence structure, and a word's syntactic category is highly relevant during language processing. Bedny *et al.* [28] suggested that the neural mechanisms engaged in thinking about event and object categories are partially dissociable. This is the case because the word category information guides the buildup of syntactic structures, namely noun phrases or verb phrases, during comprehension. Moreover, verb- argument information encoded in the verb determines the sentence structure [5].

Syntactic processing is related to the processing of lexical-semantic information at the single word level [11, 18, 25]. Indeed, syntax interacts and shares overlapping regions of activation with other levels of language processing, namely phonetics [29], complicating spatial characterization of the neuroanatomy of syntactic aspects of language processing. A summary of research articles investigating the semantics and syntax are provided in Table 2.

Studies report major activation only in the BA 44 area during syntax processing [20], but also some activation in the BA 45 [5, 18, 30-33]. Therefore, in conducting neurolinguistics research, some language-specific factors such as free word order should be considered as well.

Table 2. Summary of research papers using fMRI in the areas of syntax and semantics. Figure 2 summarizes areas found in the results these papers

	Study	Area: results	Target	Content	Subjects
1	Santi & Grodzinsky (2010) syntax [34]	Results: during syntactic comprehension, a large network of areas is engaged, but that only anterior Broca's area is selective to syntactic movement	Anterior Broca's area (BA 45) selectively adapted to movement type, while posterior Broca's area (BA 44) demonstrated adaptation to both movement type and embedding position (as did left posterior superior temporal gyrus and right inferior precentral	Sentence complexity: embedding position (right-branching vs. center-embedding), movement type (subject vs. object)	18,11F (-1 due to low behavioral scores), mean of age =23, native English speakers
2	Newman, Ikuta, & Burns Jr, (2010) Semantics & syntax [20]	The left inferior frontal gyrus (LIFG). BA 44 revealed an effect of syntactic complexity while inferior portions of the LIFG (BA 47) revealed an effect of relatedness as well as an interaction between complexity and relatedness	How the semantics relatedness of sentence constituents influences sentence processing.	A three factor design: processing phase (sentence vs. probe), syntactic complexity (object-relative vs. conjoined active) and the semantic relatedness of the nouns within the sentence	20 (15 F, mean of age = 22.9,) English native speaker
3	Pallier (2011) Semantics & syntax [18]	Temporal pole, anterior superior temporal sulcus and temporo-parietal junction showed constituent size effect only in the presence of lexico-semantic information result: proving modularity	Inferior frontal and posterior temporal regions are responsible for constituent size effects	Visual stream: 12 written words or pseudo words	40 native French speakers (23M,17 F mean= 24)
4	Hagoort & Indefrey (2014) Review Semantics & syntax [24]	Dorsal foci for syntactic processing and ventral foci for semantic processing	A clear dorsal/ventral slope in both left inferior frontal cortex and left posterior temporal cortex,	Syntactic processing semantic processing	A meta-analysis
5	Takashima, Bakker, van Hell, Janzen, & McQueen, (2014) memory [25]	The auditory and left posterior middle temporal cortices were showed by the degree to which form-only words competed during the processing of their base words. Picture-associated words showed better memory retention	Two distinct memory networks, a fast-mapping, episodic system; hippocampus, and a slower semantic memory system	Novel words, phonological forms: the form-only condition, the picture-associated condition, memory	23 F; mean =23; native speakers of Dutch

6	Bedny *et al.* (2014) Semantics & Syntax [28]	A more superior region, at the junction of the temporal and parietal cortices, responded more to verbs than to all nouns, irrespective of their semantic category. Result: the neural mechanisms engaged when thinking about event and object categories are partially dissociable.	The effects of grammatical class (verb vs. noun) and semantic category (event vs. object) by measuring neural responses to event nouns (e.g., "the hurricane").	Meaning judgment: hearing pair of words Semantics/grammatical category	18 (11 F, 7 M) (-2 due to excessive motion), mean age= 23 English speakers
7	Wallentin *et al.* (2014) Word processing [26]	Lateralization for individual tasks was found to be correlated across brain regions, but not across tasks, suggesting that lateralization may not be a unitary phenomenon, but varies across participants according to task demands	Activations in Broca's region, Wernicke's region and visual word form area (VWFA) reflect task shift costs and to which extent these effects are specific to language-related task shifts	Linguistic one-back memory paradigm; visual modality (read); auditory modality (spoken)	(n=58)
8	Rogalskya Corianne, Sprousec, & Hickokd, (2015) syntax [19]	Broca's area is not selectively processing syntactic movement, but that subregions are selectively responsive to sentence structure	Sentence processing and articulation in Broca's area, sentence-level contrasts and non-sentential comparison tasks	Sentence comprehension via syntax-specific processes, hierarchical structure building, or working memory, movement and non-movement sentences in Broca's area	15(6 M, 9 F; mean of age = 22) native English speakers
9	Huth *et al.* (2016) Semantic maps [35]	Results: detailed semantic atlas shows which semantic domains are represented in each area	Regions of the cerebral cortex: 'semantic system'.	More than 2 h. narrative stories; semantic system is organized into intricate patterns	N=7
10	Zaccarella *et al.* (2017) syntax [36]	The pars opercularis of the left inferior frontal gyrus (IFG; Brodmann Area BA 44) and a smaller region in the posterior superior temporal sulcus (pSTS). Results: BA 44 in the IFG primarily supports merge, the process of binding words together into syntactic hierarchies.	IFG; Brodmann Area BA 44, posterior superior temporal sulcus (pSTS), pars triangularis, BA 45 simple rule-based syntactic computation (merge)	Sentences, Phrases, words and syntactic hierarchy	18 (11 F; mean of age= 25.5) German speakers

Accordingly, it may not be surprising that German studies show a clear activation of BA 44 for various syntactic manipulations [29, 37, 38], whereas English studies frequently show the activation of BA 44 and additionally BA 45 [31, 34, 39]. English studies only see a clear BA 44 activation for syntactic processes in a strictly controlled experiment in which the syntactic parameters are crucial for sentence understanding [20]. It should be considered that the differences between the studies depend not only on the different languages used but also on how syntactic processes are utilized in the study as mentioned by Friederici *et al.*, 2017 [5].

The processing of linguistic structures for different levels of syntactic input, from syllable sequences to a phrase and to a sentence, was the subject of some other studies using techniques such as ERP [40, 41] or MEG [42] as well as fMRI.

According to fMRI researches included in this paper and Friederici [5], the Broca's area, in particular BA 44, and the posterior superior temporal gyrus/superior temporal sulcus are two regions of the functional network which deal with the processing of syntactically complex sentences. Similarly, other studies have identified the larger Broca's region to support syntactic processes [29, 34], and also the syntax- semantic integration of the language [24]. Others suggest the Broca's area to support verbal repetition during syntactic processes and argue that the Broca's area is not selective for processing syntactic movement, but rather some Broca's sub-regions are selectively responsive to sentence structure [19]. However, a meta-analysis over more than 50 studies revealed a functional separation of syntactic and semantic processes in the left inferior frontal gyrus. They also revealed that tasks with higher syntactic demands show stronger activation in BA 44, whereas studies with higher semantic demands show stronger activation in BA 45/47" [24].

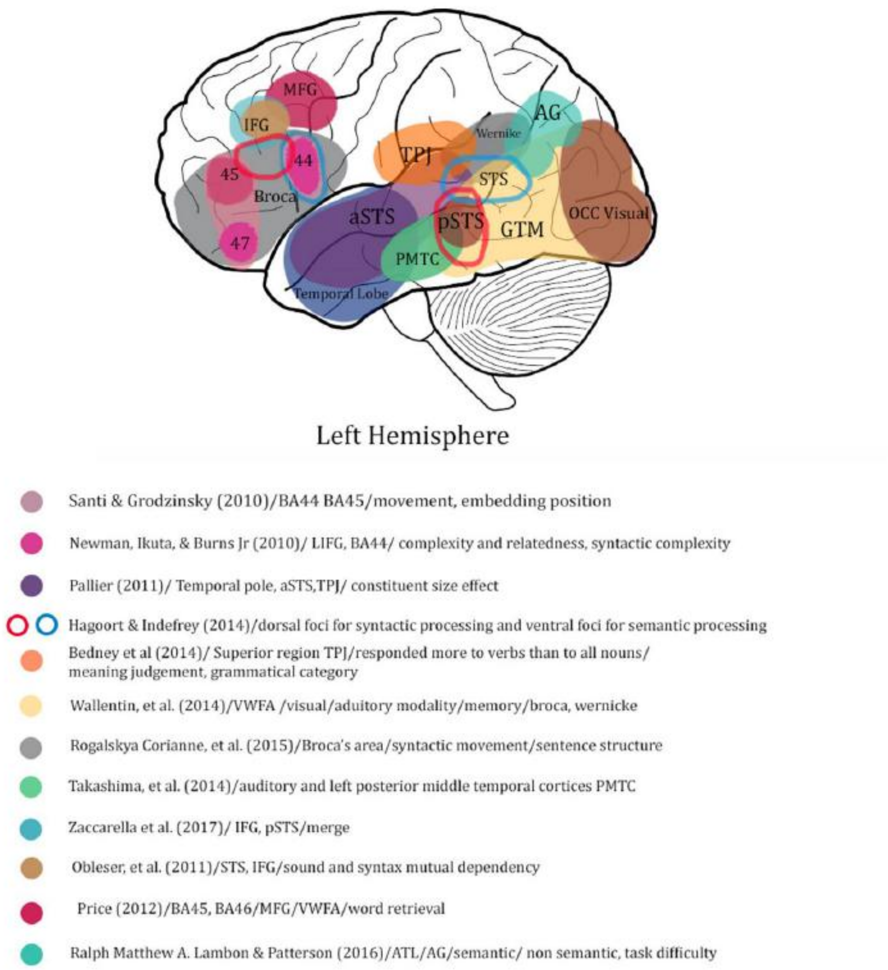

Figure 2. Results of articles using fMRI in the areas of syntax and semantics

Furthermore, in order to achieve the comprehension of complex sentences, the left temporo-parietal cortex comes into play whenever the working memory is required during sentence processing [5]. It can be concluded that BA 44 and the posterior superior temporal cortex are the main regions constituting the syntactic network.

Finally, a number of review articles have focused on neuroanatomy of language processing in human being. These articles have provided very complete information on the main aspects of language processing or have studied language processing with a different approach. For instance, Golestani, N. [43] reviewed new imagining research to investigate brain structural correlates of individual differences at low-to-high levels of the language processing hierarchy. This review is structured to describe work examining the domains, which involve increasing levels of complexity in terms of the posited perceptual/cognitive sub-functions. Mariën *et al.*[44], a consensus paper, is another example, which deals with cerebellum's role in linguistic functions. The role of the cerebellum in speech and language perception, in motor speech planning including apraxia of speech, in verbal working memory, in phonological and semantic verbal fluency, in syntax processing, in the dynamics of language production and in reading and in writing are addressed in this paper. In addition, the functional topography of the linguistic cerebellum and the contribution of the deep nuclei to linguistic functions are also discussed in this consensus paper. In another study reviewing and synthesizing the first 20 years of PET and fMRI studies, Obleser *et al.* [29] confirmed that the left anterior and the posterior Superior Temporal Sulcus (STS) and the left Inferior Frontal Cortex (IFG) were linearly more activated as syntactic complexity increased. When syntactic complexity was combined with improving signal quality, this pattern was replicated. Also, in a recent large-scale meta-analysis by Ralph Matthew A. Lambon, J. E., & Patterson, K. [27], it is indicated that the Anterior Temporal Lobe (ATL), that is, the semantic region, shows deactivation for non-semantic and the Angular Gyrus (AG) shows task-difficulty correlation. The results of this meta-analysis introduce Controlled Semantic Cognition (CSC).

4. Conclusion

This paper reviewed many neuroscientific studies on language processing. In conclusion, it should be mentioned again that the experimental methods in studying language such as fMRI and other neurolinguistics techniques could provide scientific evidence for proving theoretical assumptions. For example, the basic syntactic computation of binding two elements into a phrase (called Merge) assumed by linguistic theory can be evidenced at the neurobiological level in a confined brain region, BA 44" [5, 36]. Besides, results of such researches can help other scientific developments as brain mapping according to cognitive functions such language and memory, etc. can provide a guide in the pre-surgical planning on neurosurgery. Speech therapists and software designers should consider the results of neurolinguistics research, too.

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