Not single brain areas but a network is involved in language: Applications in presurgical planning

Razieh Alemi[a,b], Seyed Amir Hossein Batouli[a,c], Ebrahim Behzad[a], Mitra Ebrahimpoor[c], Mohammad Ali Oghabian[c,d,*]

[a] Department of Neuroscience and Addiction Studies, School of Advanced Technologies in Medicine, Tehran University of Medical Sciences, Tehran, Iran
[b] Department of Otorhinolaryngology, Faculty of Medicine, McGill University, Canada
[c] Neuroimaging and Analysis Group, Tehran University of Medical Sciences, Tehran, Iran
[d] Medical Physics and Biomedical Engineering Department, Tehran University of Medical Sciences, Tehran, Iran

ARTICLE INFO

ABSTRACT

Objectives: Language is an important human function, and is a determinant of the quality of life. In conditions such as brain lesions, disruption of the language function may occur, and lesion resection is a solution for that. Presurgical planning to determine the language-related brain areas would enhance the chances of language preservation after the operation; however, availability of a normative language template is essential.
Patients and Methods: In this study, using data from 60 young individuals who were meticulously checked for mental and physical health, and using fMRI and robust imaging and data analysis methods, functional brain maps for the language production, perception and semantic were produced.
Results: The obtained templates showed that the language function should be considered as the product of the collaboration of a network of brain regions, instead of considering only few brain areas to be involved in that.
Conclusion: This study has important clinical applications, and extends our knowledge on the neuroanatomy of the language function.

1. Introduction

Transferring one's intentions to others by producing structured and complex acoustic signals is regarded as the language ability. Language has evolved tremendously since its first usage at about 50 thousand years ago, and alterations in symbolic units, syntax, and the rules of combining different vocal units for constructing final meaningful words and sentences have led to the emergence of various languages [1,2].

Language function is considered to include the three modules of phonology, semantic and syntax [3,4]. Phonological function refers to the use of sound features for producing specific linguistic units or their combinations; semantic function is required to understand the meaning and contents of the abstracted vocal units [5]; and syntactic function is necessary for comprehending/producing a phrase or preparing a well-structured sentence [6,7]. Although easily classified, language is beyond simply mixing words and building sentences [5], and therefore devoting a seat in the brain for this function is a challenge [8,9].

Language is one of the five most essential functions of the human brain [10]; however, this function could be seriously deteriorated in

certain conditions such as brain lesions or tumors. One main solution to brain lesions is surgical resection, but removal of the abnormality should happen with the minimum risk of inducing neurological deficits, e.g. language distortion, after surgery [11]. Presurgical Planning (PSP) is a process performed to assess the feasibility of the surgical removal of brain tumors, and tries to balance the maximum resection of the tumor while preserving the highest function of the patient. PSP is performed by identifying brain neural networks relevant to a specific function, and by estimating the distance between the lesion and the eloquent brain areas: in distances less than 10mm the chances of language deficit significantly rises [12]. Functional Magnetic Resonance Imaging (fMRI) is one of the best approaches used in PSP, as it can predict the potential risks of surgery on any human function, such as language [13–16], determine the dominant hemisphere of the brain for that function [11], and efficiently guide the neurosurgical procedure [17].

Mapping the brain areas associated with a particular function, e.g. for localization of language-related brain areas in PSP, needs availability of a standard reference. We comprehensively surveyed the literature in search of a normative template for the language function, and

72 studies on healthy subjects were identified. The major outputs of these studies were illustrating the essential brain regions responsible for different components of the language function, developing optimized fMRI language tasks, investigating the laterality of brain language function, testing variability of fMRI activation areas among populations, and testing the influence of age and sex on language functionality. Despite all, there had been constraints in one or more aspects of these studies, which limited their consideration as a standard template: 53 of these studies recruited less than 20 participants (only 6 studies with #participants > 50), 30 of the studies investigated only one aspect of the language function, and 44 studies were performed on 1.5T MRI scanner. Besides, robust clinical assessments of the health status of the participants, and a narrow age range, were rarely observed in these studies.

In addition to the above-mentioned limitations, regarding brain variability between phenotypically-different populations (i.e. races) [18,19], as well as regarding fundamental differences between the languages [20], such as the Persian language (as an Indo-European language) being read and written from right to left [21], implementing a template obtained from a different population to our Persian patients could impose substantial biases to the clinical outcome. As a result, providing a population-specific language template is necessary.

This study, using a large sample of healthy participants, aimed at identifying brain regions involved in the three main components of the language function including sentence comprehension, semantic, and production. All aspects of the study were accurately selected so that the outputs could be regarded as a standard template of the language function, applicable to clinics. Also, the laterality of the language in brain, any overlap/differences between the networks of the three templates, as well as any gender influences were investigated.

2. Patient and methods

2.1. Participants

Recruitment of the participants was through public advertisement. A 9-page questionnaire was prepared by a physician of the group, based on the inclusion/exclusion criteria of the International Consortium for Brain Mapping (ICBM) [22], which comprised the following sections: a) telephone screening, b) demographic and medical questionnaire, c) exclusion criteria, d) clinical assessments and e) Mini-Mental State Examination [23]. In brief, the inclusion criteria were: age range between 20 and 30 years old, being Right-handed (based on the Edinburgh Inventory [24]), minimum 14 years of education, and Persian race. The applicants were excluded due to any current or past chronic or acute Neurologic or Internal disorder, medicine consumption, surgery, or trauma; being overweight (over one-hundred Kilograms); having a serious family history of any disease; being smoker or drug/alcohol abuser; being claustrophobic; or having implants or any other metal objects in the body.

Based on the above criteria, we recruited 72 participants, of which 12 data were finally excluded due to excessive motion or problems in hearing the auditory tasks. This resulted in a sample size of 60 (31 M), with the mean age of 25.16 (± 3.2) years (Male: 25.03 ± 2.91; Female: 25.39 ± 3.66), and mean education of 16.67 (± 1.78) years (Male: 16.83 ± 1.53; Female: 16.63 ± 1.58). There was no significant male-female differences regarding age or education.

This study was performed in agreement with the Ethics Statement of Tehran University of Medical Sciences [25]. All participants declared their assent during the telephone interview and after being informed about the general aim of the study, and they signed their consent forms on the test day. A gift card was presented to the participants for appreciation of their participation.

2.2. fMRI task stimulus

A thorough review of the literature, as well as our previous studies and experiences in the field [11,26–29], in addition to a report by the American Society of Functional Neuroradiology (ASFNR; https://www.asfnr.org) on the most efficient fMRI language tasks [30], led us to selection of three covert language stimulus paradigms in this study, including Expressive, Receptive, and Semantic paradigms, to comprehensively cover most aspects of the language function.

2.2.1. Expressive paradigm

This paradigm was to activate brain areas related to speech production. The Word Production (WP) task was selected for this paradigm [11,27], which included 4 control and 4 act blocks, each lasting 24 s, resulting in a total stimulus time of 3:12 min. Each control block consisted of four runs of the following sequence: 4 Japanese alphabets each for 1sec + 2sec blank white page, and each act block consisted of 4 Persian alphabets each for 1sec + 2sec blank white page. The Persian alphabets were displayed with black fonts on a white background, with the same size and characteristics as the Japanese alphabets. The participants had to add the 4 alphabets together to produce a word and read it silently.

2.2.2. Receptive paradigm

The Auditory Responsive Naming (ARN) paradigm [31–33] was selected to activate the brain areas involved in perception of meaningful short sentences, and it had similar number of blocks and time length to the WP task. In the act block, the task included 4 times presentation of a sound lasting for 3 s, followed by 3 s of silence. The control block consisted a similar sequence, with the difference that the sounds were played in a reverse and therefore ambiguous order. This task included 16 sounds, each being a sentence read by a male member of the lab, recorded in a professional sound studio for maximum quality of the sounds. All these sentences were between 6 to 9 syllables, and included implications such as "*This is the capital of Iran*", "*This is the first season of the year*", and "*We lock the door with this*". The sentences were not read as a question, but the participant by listening to them and perceiving their meaning could find an answer for it and respond the answer silently.

2.2.3. Semantic paradigm

The Visual Semantic Decision (VSD) paradigm [34] was selected to activate the brain areas related to semantic language. The number of blocks and the overall duration of this task was similar to the other two tasks. Here, the participants were responding to questions using a response key, and only the correct responses were selected for their data analysis. During the control block, 8 images, each lasting for 3 s, were presented to the participants. The images included two objects consisting of parallel lines in vertical (|||||) or skewed (/////) directions, randomly distributed. The participant had to press the buttons using his/her thumb or small fingers if the two objects were similar or different, respectively. During the act block, the same number of images were presented, and each image included two words, which the participant had to read and respond whether they could be regarded to be of the same or different categories; examples include "*food – pasta*", and "*food – shoe*", respectively.

2.3. Imaging

A checklist was followed by the examiner before each MRI scan, to confirm performance of the telephone screening, not consumption of any doping food (e.g. coffee, alcohol) or medicine by the participant on the exam day, not consumption of any Antineuropathic pain drug, performance of complete clinical checks by the physician, setting lenses for a better visualization of the goggle (if required) as well as goggle cleanness, training the participant with his/her language tasks, asking

the participant to respond silently to the questions with no mouth motion, setting the headset volume on a preset level, and accurate performance of the response box.

Magnetic Resonance Imaging of the brain was carried out using a SIEMENS 3 T MRI scanner (MAGNETOM Trio; Siemens Healthcare GmbH, Federal Republic of Germany) with an 8-channel head coil at the Medical Imaging Center, Imam Khomeini Hospital, Tehran, Iran. A 32-channel head coil was also available, however, smaller size of this coil limited the use of goggles and headphones for the participants. Functional T2*-weighted images were collected using blood oxygen level dependent (BOLD) contrast (TR = 3000ms, TE = 30 ms, flip angle = 90˚, FOV = 192 mm^2, matrix size = 64 × 64, voxel size = 3 × 3 × 3mm, and slice gap = 0 mm). Prior to the functional scan, a T1-weighted anatomical image was acquired, using a gradient echo pulse sequence (TR = 1800ms, TE = 3.44 ms, flip angle = 7˚, voxel size = 1 × 1 × 1mm, FOV = 256 mm^2, matrix size = 256 × 256, and slice gap = 0 mm). After the scan, the participant was questioned about clear presentation of the visual and auditory stimulations during the scan, and his/her responses to the questions of the WP and ARN tasks were written down.

To present the images and sounds to the participants during the scan, a goggle (800*600 pixel resolution in a 0.25 square area and refresh rate of up to 85 Hz) and earphone (30 dB noise-attenuating headset with 40Hz to 40 kHz frequency response), which were suitable for up to 4.7 T magnetic fields were used (VisuaStim, The Pennsylvania State University, USA). An MR compatible Response Box was also used for recording participant's responses to the questions during the scan. Presentation of fMRI tasks to the participant was synchronized with the scanning, using the trigger pulse of the MRI scanner.

2.4. Data analysis

2.4.1. Pre-processing

All MRI data preprocessing were conducted in FSL (the FMRIB Software Library) v5.0.8[1] [35]. Functional data went through several preprocessing steps. First, fieldmap-based unwarping of EPI was applied (Effective echo spacing: 0.256 ms., EPI TE: 30 ms., unwarp direction: -y, 1% signal loss threshold) using PRELUDE + FUGUE [36]. Next, motion correction was performed using MCFLIRT [37]. In addition, to prepare statistical group analyses all images were normalized to the Montreal Neurological Institute (MNI) T1-weighted template using FLIRT [37,38] in two steps: for each subject, first an example fMRI image was registered to the same individual's high-resolution T1-weighted image using BBR algorithm. Second, the high resolution image was registered to the MNI standard template using a 12˚-of-freedom (DOF) transformation. These two steps were then combined into one registration matrix which was used to register the EPI images into the MNI space. The coordinates (x, y, z) of activities in this study are therefore reported in the MNI space. All registration results were manually inspected to guarantee valid registration. Finally, the images were spatially smoothed using a Gaussian kernel with a Full Width at Half Maximum (FWHM) value of 5 mm. Structural images were skull-stripped using BET [39] and segmented into white matter (WM), gray matter (GM), and cerebrospinal fluid (CSF) using FAST [40]. The individuals' binarized GM, WM, and CSF masks were projected to MNI space using inverse registration matrices that were created earlier and then were averaged to generate study-specific templates of different tissue types.

2.4.2. Independent component analysis

For each task, the group inferences were made based on Independent Component Analysis (ICA). In this paper, we used GIFT v4.0a[2] (Group ICA of fMRI Toolbox), an application developed in

MATLAB[3] R2014a (Mathworks Sherborn, MA, USA), with a two-step principal component data reduction, Infomax ICA [41] with ICASSO: software for investigating the reliability of ICA estimates by clustering and visualization [42] and subsequent back-reconstruction [43]. ICA is a popular data-driven approach to distinguish temporally coherent and spatially independent networks that underlie fMRI activity [44]. This method is proved to be effective in detecting task-specific activations in fMRI data [45–47]. A number of ICA algorithms are used for fMRI data analysis, and Infomax is one of the most commonly used, as it is highly reliable and shows similar results to the General Linear Model [48,49] for the task-related data. Although Infomax is illustrated to be consistent in repeated runs, it is a stochastic process and gives slightly different results for each iteration. In order to arrive at a robust decomposition, we adopted ICASSO method as implemented in GIFT. ICASSO repeats the ICA algorithm several times (we used 100 runs); each run results in a different set of components. Subsequently, the estimated components of all runs were hierarchically grouped into clusters based on spatial information and higher-order statistics [50]. Reproducibility of the components was evaluated according to cluster quality index (Iq) of each component. We indicated the optimal number of components for each group ICA based on MDL (modified minimum description length algorithm) criterion [51]. Last step of the analysis included back-reconstruction. Data reduction matrices from the first step and the resulting mixing matrix were used to create individual subject maps. Resulting individual maps were used to draw statistical inferences about both single subjects and groups of subjects [43]. We chose a significance threshold of p < .05, FDR corrected for all analyses. Only correlated (positive) language regions were included in the results.

2.4.3. Post-processing

We selected the components using the following procedure: nuisance components were identified and discarded; among the remaining components, we selected those that were task-related; and lastly, language-related components were identified.

The Multiple Linear Regression (MLR) algorithm, implemented in GIFT, was used to sort the components based on their spatial and temporal properties. Spatial sorting was performed to compare the spatial pattern of the ICs with the WM, CSF and GM templates created based on the high-resolution images of all participants. ICs were ordered based on their correlation coefficients (R^2) for each template, and those with a high correlation value with CSF or WM were considered artifacts, and others were considered independent components of interest (ICOI). We chose a threshold level of $R^2 > 0.05$ based on literature [47,52,53].

Temporal sorting, implemented in GIFT, regresses the design matrix of the task over each IC's time-course and estimates a beta-weight for each task condition. We convolved a box-car design based on task blocks with the canonical hemodynamic response function to create our design matrix. A greater beta-weight indicates an increase in task-related activity in the IC [54]. Lastly, we performed a one-sample t-test on the beta-weights of the subjects against zero using SPSS. ICs with a beta-weight showing significant difference were considered as task-related independent components (TRIC).

Our focus was to compare the activation patterns revealed by each language task. To determine the components associating with language, we used Talairach labeling system, where Talairach coordinates for positive regions of each IC were reported [55–57]. Then, images were averaged to form one representative component. There are several methods to deal with multiple components representing similar networks, but we chose averaging, as the spatial characteristics of language region (i.e. localization) was of our interest. Further analysis was

---

[1] http://fsl.fmrib.ox.ac.uk/fsl/fslwiki/.

[2] http://icatb.sourceforge.net.

[3] http://www.mathworks.com.

performed on the selected language-specific independent components (LSIC) of each task. All these components had high reliability as indicated by ICASSO results.

Resulting group maps of ICA were arbitrary thresholded. For a solid group inference, back-reconstructed spatial maps of each selected component for all individuals entered a second-level (random-effect) one-sample t-test. To reduce multiple comparisons error, one-sample t-test was only performed on LSICs. Another two-sample t-test was used to detect gender effects for each task.

To study the laterality of the three tasks, a voxel-wise laterality map was created for each task. Images were flipped in the left/right direction and subtracted from themselves [58]. This was done using the LUI software[4]. Then, one-sample and two-sample t-tests were computed for the lateralized images of the tasks. It is worth noting that a voxel-wise laterality index is not sensitive to thresholding and idle for ICA based analysis.

3. Results

3.1. Activation maps relevant to the ARN task

Forty-one ICA components were identified for the ARN task, where 18 were ICOI[5] (i.e. not associated with white matter or CSF). Of these, 10 were TRICs[6] (i.e. beta-weights were significantly greater than zero). There were 4 components relating to Brodmann's areas 22, 44 & 45. One-sample t-test was performed over back-reconstructed subject images of the respective components.

Fig. 1 demonstrates brain activations resulted by the ARN task (including the main functional language regions: BA 22, 44, 45), along with their time-series plots. As it shows, BA 44 and 45 (left hemisphere) were remarkably activated, as well as some degree of activation for their corresponding regions in the right. BA 22 also showed activation, with a larger amount of activation in the right hemisphere compared to the left.

There were also other brain areas activated during the ARN task, including bilateral superior frontal gyrus, medial frontal and orbital gyri, parts of cingulate gyrus, postcentral gyrus, and superior temporal gyrus. Some brain areas in the right hemisphere including middle frontal gyrus, superior and inferior parietal lobule, angular and supra-marginal gyri, middle temporal gyrus, cuneus, and precuneus were also active, as well as insula in the left hemisphere. Details of the active brain areas associated to this task are provided in Table 1.

3.2. Activation maps relevant to the VSD task

Forty-four ICA components were estimated in the analysis of this task, where 15 were noise-free, and 8 were TRICs. We detected 3 LSICs[7]. Fig. 2 shows the cortical localizations of these LSICs based on t-test results and their respective time-series plots. Here, VSD task produced robust activations in BA 44 and 45, with no considerable activation in their corresponding areas in the right hemisphere. Similar to ARN task, strong activations were observed in the corresponding area of BA 22 in the right hemisphere, and not in the left.

Other brain areas activated during this task are listed in Table 1, and included bilateral cingulate gyrus, inferior parietal lobule, superior and middle temporal gyrus, cuneus and precuneus. Also, dorsolateral pre-frontal cortex and inferior frontal gyrus in the left hemisphere, and superior parietal lobule, angular and supramarginal gyri, lingual gyrus and fusiform gyrus in the right were active.

3.3. Activation maps relevant to the WP task

Thirty-nine ICA components were detected here, and 22 were discarded as noise. Of the 17 ICOIs, 9 were associated with the task, and 5 LSICs represented BA 44, 45, and 22. Fig. 3 displays the temporal and spatial characteristics of these ICs. Both BA 44, 45 and BA 22 were significantly active here, again with higher strength and extension of activation for BA 22 in the right hemisphere.

Table 1 provides the list of other brain areas active during this task, including bilateral postcentral gyrus, inferior parietal lobule, superior temporal gyrus, and auditory cortex. In addition, activation was observed in the right hemisphere in the regions including angular and supramarginal gyri, middle and inferior temporal gyri, and fusiform gyrus.

3.4. Laterality

To investigate the laterality of brain activations in our language paradigms, we performed a test for statistical difference of brain activations between the two hemispheres. The results of this analysis are illustrated in Fig. 4. As is observed, in all three tasks, BA 44 and 45 were significantly more active in the left hemisphere, similar to the corresponded area of BA 22 in the right. Therefore, a notable dominance of BA 4445 activation in the left, and substantial predominance of BA 22's right-corresponding area's activation were illustrated.

3.5. Task comparison

Fig. 5 shows a high overlap between brain activations relevant to our three language tasks in detecting BA 44 and 45. The similarity in the extent and intensity of activation of BA 44, 45 in ARN and VSD tasks is notable, with minimally higher intensity in the center of the node in the ARN task. Meanwhile, the WP task clearly showed more strength in activating this region, especially in BA 45, and orbital part of inferior frontal gyrus. The corresponding region of these areas in the right hemisphere showed scarce activation in ARN and VSD, whereas this region was obviously activated in the WP task.

Comparing the tasks for activating BA 22 showed less robust overlaps (Fig. 5). While ARN and WP tasks were able to activate BA 22, albeit with higher strength in WP, VSD was not. In addition, activation of BA 22's homologue area in the right hemisphere was considerable in all three tasks, again with a higher strength in WP task compared to the other two tasks.

3.6. Gender effects

As per the results of a two-sample t-test, there were no significant differences between the two sexes in activating the main language regions by any of the three tasks.

4. Discussion

4.1. Summary of the results

The initial aim of this study was to develop a normative template of the language function in a young and healthy Persian population, with its major application in clinical purposes and especially in PSP. We selected three language paradigms which covered most aspects of the language function, and three standard brain maps were produced accordingly. In addition, laterality of the language function was tested, the overlap of brain regions involved in the three tasks was examined, and any gender differences in brain language function was evaluated.

The constructed templates implied that the idea of considering the language function to be only dependent on the Broca's and Wernicke's areas might need to be replaced by considering this function as the product of a collaboration between a number of brain regions. The shift

---

[4] http://mialab.mrn.org/software.

[5] Independent Component of Interest.

[6] Task-Related Independent Components.

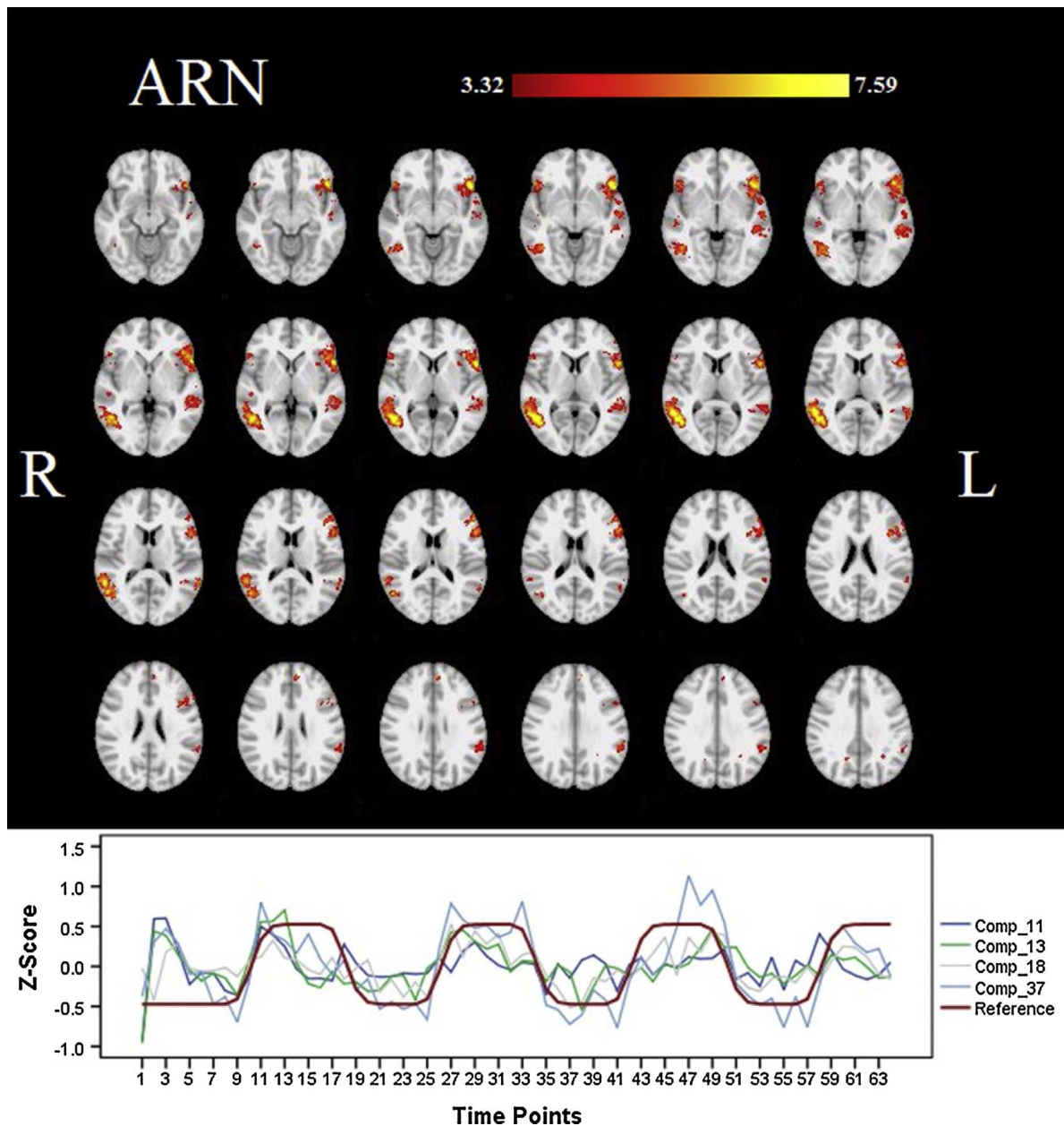[7] Language-Specific Independent components.

Fig. 1. The localization of brain activations of healthy participants during the ARN task. The upper part displays spatial extension of one sample t-test results for the language-specific ICs (FWE correction, p < 0.05, and cluster extension of 25 voxels). The lower part shows the mean time-courses of the corresponding components. All time courses are scaled to z-scores. R: right; L: left; ARN: Auditory Responsive Naming.

of focus from core areas to the concept of a network for the language function is suggested by others as well [59], and current studies endeavor to reveal the mechanism of cooperation between functionally- and structurally-connected brain areas in the language function [60].

4.2. Receptive network

Our results showed numerous brain regions to be involved in the language comprehension during the ARN task. The core brain regions responsible for understanding the auditory contents are introduced to be BA 22, 44 and 45 [61,62], in agreement with our results. However, the involved areas are not confined to them, and our results included bilateral superior frontal gyrus, medial frontal gyrus, orbital gyrus, parts of cingulate gyrus, and postcentral gyrus, as well as several areas in the right hemisphere including middle frontal gyrus, superior and inferior parietal lobule, angular and supra-marginal gyri, middle temporal gyrus, cuneus, and precuneus.

The neural processing steps for an auditory sentence comprehension include phonological processing of the words [63,64], word-form recognition finding [65], semantic and syntactic processing of the contents, prosody, and intonation [66]. These functions depend on a vast bilateral network [67,68], and this is one explanation for the extended brain network observed for this function in our study.

It is widely accepted that bilateral STG are golden sites for auditory language processing, in which the anterior part is engaged in syntactic processing [69] or word recognition [65], and the posterior part as well as the angular gyrus and even anterior temporal lobe have some roles in sentence processing and word prediction in a sentence [64,70–72]. They are also assumed to be relevant to the inner speech area [65]. Here, the strong activation in the right STG reflects the vast semantic processing network, which also takes advantage of the right hemisphere supply.

Table 1
The characteristics of the clusters of activation for the three language stimulus tasks: right or left hemisphere; number of voxels; maximum t-value; and the coordinates (X,Y,Z) of the activations in the standard MNI space.

# Cluster	R/L	# Voxels	Max t	X	Y	Z
ARN Task						
12	L	1426	10.4	−46	24	−8
11	R	1302	10.4	50	−58	6
10	L	580	6.28	−52	−32	−2
9	R	158	6.6	52	26	−6
8	R	137	5.77	18	−56	40
7	L	94	5.25	−56	−14	−6
6	L	92	5.28	−44	2	54
5	L	39	4.63	−6	20	60
4	L	37	4.78	−4	−2	68
3	L	31	5.83	−6	46	28
2	L	27	4.53	26	−76	−38
1	L	26	4.91	−30	−54	36
VSD Task						
9	L	868	8.5	−46	10	−2
8	R	541	10.2	48	−66	16
7	L	144	5.78	−8	12	68
6	R	94	6.06	52	20	−6
5	L	54	5.56	−8	38	22
4	R	35	5.41	10	20	44
3	R	34	5.1	40	14	4
2	L	32	5.83	30	−58	34
1	R	26	5.05	−28	54	26
WP Task						
11	L	2774	12.3	−46	20	−4
10	R	2022	10.7	54	−32	4
9	L	825	8.68	−58	−46	14
8	R	663	7.12	50	32	0
7	L	403	6.58	−58	−50	28
6	L	137	5.85	−26	52	24
5	L	110	5.31	−60	−6	−6
4	L	65	4.96	−44	−70	−16
3	L	62	4.18	−22	4	−12
2	L	58	4.83	−44	−52	−16
1	L	44	4.54	−46	4	−18

ARN: Auditory Responsive Naming; VSD: Visual Semantic Decision; WP: Word Production.

We also found strong activations in the left IFG and its homologue area in the contralateral hemisphere. There are numerous studies which suggest the contribution of bilateral IFG in language comprehension [66,73–78]. The involvement of BA 44 and 45 in language perception seems to be different in nature, in which BA 44 is more engaged in the syntactic processing of a sentence [55] whereas BA 45 serves the semantic process [66]. Generally, It has been argued that these area has pivotal roles in motor function [79], sensory-motor integration [80,81], modulation of auditory input [72] or increasing perception [82], attention [83], and verbal working memory [84]. Recently, Hargoot provided more evidence supporting his model in favor of the engagement of these areas in unification [85]. Regarding all these different dimensions of view to the contribution of IFG in auditory language processing, we concluded that this area operates as a core area which simultaneously or serially processes information in a feed forward or feedback manner, while connected to STG.

The other critical region which was activated in our ARN task was bilateral BA 6. The exact role of this area in auditory processing is not clear, although there are structural and functional connections between this area and other language-related brain regions [86,87]. In line with the present results, there are many other studies that report activation of this region in auditory processing [88–90], especially when participants are encountered with sentences [91–95]. We suggest that activation of BA 6 in our ARN task could be related to motor representation of sounds in sentences, proposing that the brain uses learned motor representations in order to increase the speed of sentence

comprehension, and save time.

Activation of right parietal lobe may be related to its contribution in connecting sensory and spatial information to the motor system, as suggested previously [96]. Also, activation in MFG and BA 9 could be related to auditory spatial localization [97] or working memory paradigms [98]. The contribution of posterior hetromodal cortex supports semantic processing [99] and has some role in lexical semantic access and integration, due to its connections with IFG [100], although in the present study these activations were limited to the right hemisphere. Interestingly, there are some evidence that the right hemisphere might be more subtle to semantic relations versus the left [67]. Additionally, we observed bilateral activations in temporal pole, BA 38, which is in line with other studies [62,101], even though Josse claimed that activation of the left temporal pole is a sign of leftward functional lateralization, regardless of its right contribution [102].

4.3. Semantic network

To determine brain networks relevant to language semantic processing, we used a word category semantic judgment task, in which the participants had to use their semantic knowledge to make associations between the visually presented words and their categories. Our VSD task showed that the strongest activations relevant to the mental demonstration of human lexicon were observed in the right BA 22, left IFG (BA 4445,47) and left MFG (BA 9,10,46). Besides, bilateral cingulate gyrus, inferior parietal lobule, STG, and MTG were observed active, suggesting the role of an extensive network of brain areas in both hemispheres for semantic processing.

Numerous theories are proposed to determine a seat in the brain for semantic decisions. While some declare that there are 'semantic hubs' in the frontal, temporal or parietal cortices [103], others defend their arguments about devoting each word categories to different parts of the brain [104].

IFG, and especially BA 45 and 47, have an essential role in semantic processing in the healthy brain [99,105], although there are debates on that. For example, Thompson-Schill [106] claimed that the nature of demands on the semantic task could influence the degree of IFG activation. She further concluded that the activation of left IFG only represents the engagement of whole prefrontal system in semantic processing [107], whereas Booth proposed that the semantic information represented in MTG encounter some form of manipulations in IFG [108].

Recently, Tomasello, using a neural network model, proposed that some brain areas have a pivotal role in semantic processing, and do take advantage of other areas participating in category-specific processing [109]. We suggest that bilateral BA 44 and 45 have an important role in phonological and general semantic processing, and dorsolateral prefrontal cortex (BA 9, 46, 47) is involved in the memory, executive function, and the decision makings related to selecting the word category. Since these two areas have connections with STG, posterior parietal cortex, anterior and posterior cingulate and premotor cortex, the suggestion seems feasible. In addition, the activations in bilateral BA 22, 38, and 21 were noticeable here, and there are reports that these areas are critical for semantic representations [110].

The activation of temporo-occipital regions observed here, such as in the right fusiform gyrus, parahippocampal gyrus, and bilateral visual associative cortex, might be related to word processing and visual imagery of the visually presented stimuli, which is more likely related to memory, rather than semantic processing. Bilateral temporo-parietal zone, BA 39 and 40, were also active here, and these areas are in a common network for multimodal semantic representation and concept retrieval, as Friederici has claimed that these areas put separate items into a whole concept [69].

Cingulate gyrus was also bilaterally activated here, as well as the dorsal posterior part of it, i.e. precuneus. Their activation may be due to visual imagery [111], or due to their reciprocal connections with
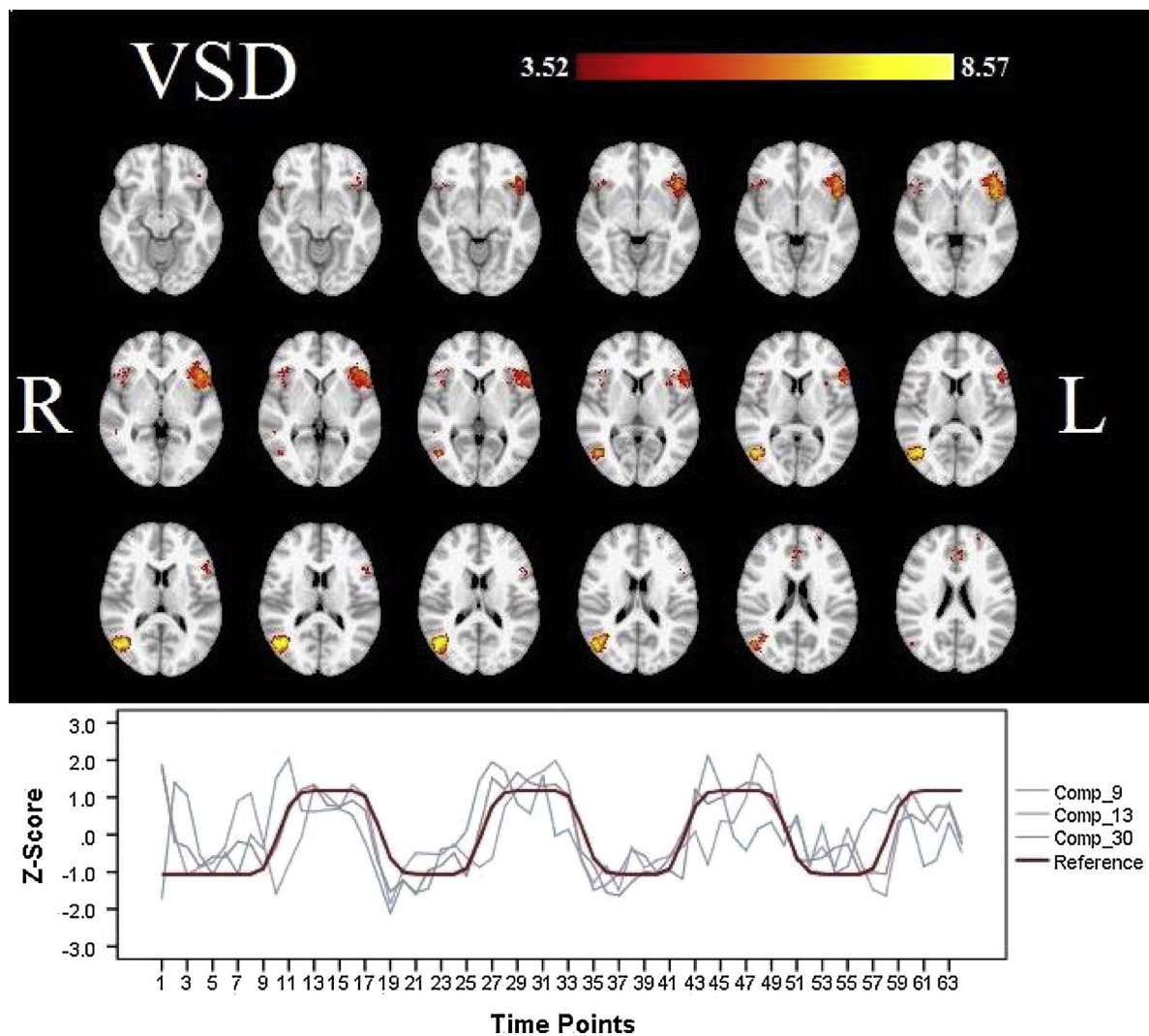
Fig. 2. The localization of brain activations of healthy participants during the VSD task. The upper part displays spatial extension of one sample t-test results for the language-specific ICs (FWE correction, p < 0.05, and cluster extension of 25 voxels). The lower part shows the mean time-courses of the corresponding components. All time courses are scaled to z-scores. R: right; L: left; VSD: Visual Semantic Decision.

hippocampus [112,113], associating their function with episodic memory and visuospatial functions [114–117]. Therefore, it is suggested that these regions act as a bridge between word memory encoding system and their episodic retrieval.

Here, the nature of bilateral activation could be the reflection of an integrated approach between the two hemispheres in semantic processing [118]. Interestingly, it has been proposed that the degree of laterality is related to the type of input; for example, non-verbal inputs increased activation in the right hemisphere rather than the left [119]. On the contrary, there are some arguments about equal participation of both hemispheres in semantic processing, with no priority for words or pictures [120,121]. Similarly, some studies report that the semantic processing is 'amodal' in the two hemispheres [122,123], whereas in our VSD task BA 22 was more significantly activated in the right.

Our suggestion is that both hemispheres participate in semantic processing, albeit in different representations of the words. For example, the left BA 22 has a critical role in the semantic coding of the information which will be processed in BA 44, 45. These areas are more structurally and functionally connected together in the left hemisphere, leading to their higher engagement in incorporating the phonological and semantic processing of word stimuli, and in relating each abstract word concept to its lexicon. In contrast, BA 22 in the right hemisphere could be more engaged in recognition of word categories or conceptual

knowledge processing.

4.4. Expressive network

Our results showed numerous brain regions to be involved in language production during the WP task. The core brain regions included BA 44, 45, and BA 47 in IFG. One of the nominated brain areas for producing language is inferior frontal gyrus [21,124,125], in agreement with our results. In our study, subjects had to focus on producing meaningful words in a letter by letter manner and by utilizing orthographic to phonological transformations, and our results are similar to those studies that used a covert paradigm for monitoring language expression areas [126,127].

In an Electrocorticographic (ECoG) recordings study using word production tasks, it was shown that there is a flow of the neural representations of a spoken word between the sensory areas and prefrontal cortex, in which BA 44 and 45 were engaged in phonological processing and articulatory encoding [128]. Also, other studies showed that the connection between BA 44 and parietal lobe could support speech fluency [129], whereas BA 45's activation was regarded to deal with making semantic choices [107].

Moreover, BA 22 was active in our WP task in the left hemisphere, and even more strongly in the right. In line with other investigations,
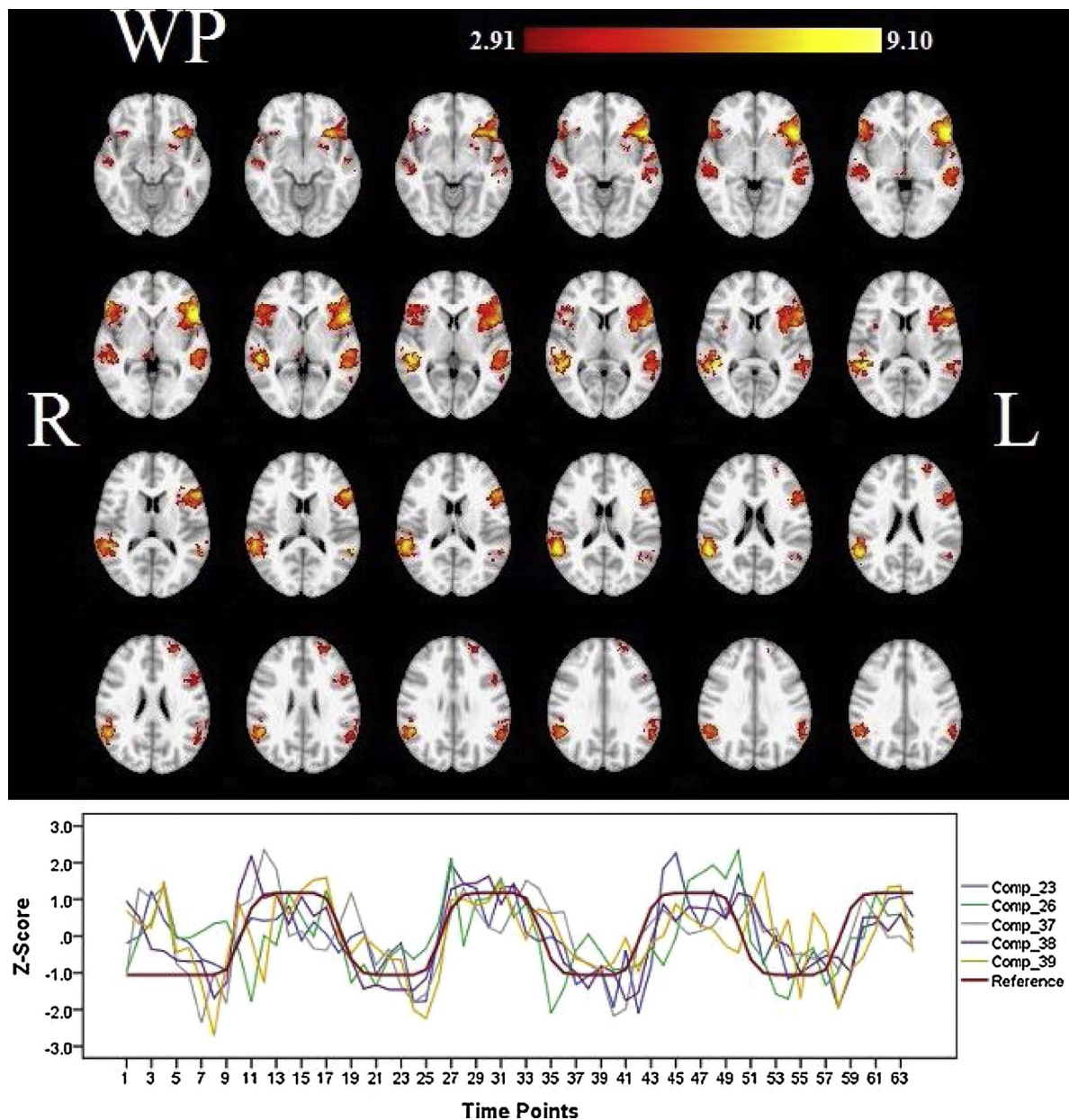
Fig. 3. The localization of brain activations of healthy participants during the WP task. The upper part displays spatial extension of one sample t-test results for the language-specific ICs (FWE correction, p < 0.05, and cluster extension of 25 voxels). The lower part shows the mean time-courses of the corresponding components. All time courses are scaled to z-scores. R: right; L: left; WP: Word Production.

the activation of STG in covert word production reflects the incorporation of different brain areas as a network for language expression [63]. More than a decade ago, using PET imaging, Scott proved that phonetic processing is performed in the left STG [130]. Despite disagreements [131], Buchsbaum suggested a partially shared input/output phonemic level in processing and producing language [63]. Similarly, Okada, using a single word production task, showed that the left dorsal superior temporal lobe was activated in all their ten subjects, which lead to this concept that there is an overlap between language perception and production systems, emphasizing the engagement of posterior temporal lobe in phonological processing [132]. Furthermore, Price argued that this co-activation might be due to auditory association or feedback between these areas [126], although there was no auditory stimulus in their study design, which is a fundamental property of language expression. In addition, this co-activation is associated with the experienced auditory connection [133]. Although the stimulus was visually presented in our WP task, as the specific role of this area is

related to phonology and semantic processing, this area will be activated when encountering with such a stimulus, regardless of the nature of the stimuli [134].

Other brain areas that were observed active during this task confirm that a vast network of brain areas incorporate in language expression. Bilateral postcentral gyri, BA 2 and 3, inferior parietal lobule, BA 39 and 40, primary and secondary auditory areas, BA 41, 42 and insula, and BA 13 and 41 were active here. Right inferior temporal gyrus, BA 19, and fusiform gyrus were also among them. It seems that these regions are in a common network for single word production, which is mentioned in other studies as well [132,135–144].

Since in our WP task participants had to keep the phonemes in their memory system and combine them in a semantic prediction manner based on their experience, it is not far from this conclusion that there are joint demands of phonological and semantic processing. As a result, engagement of a vast number of brain regions here could reflect their involvement in the working memory system. The activations in the
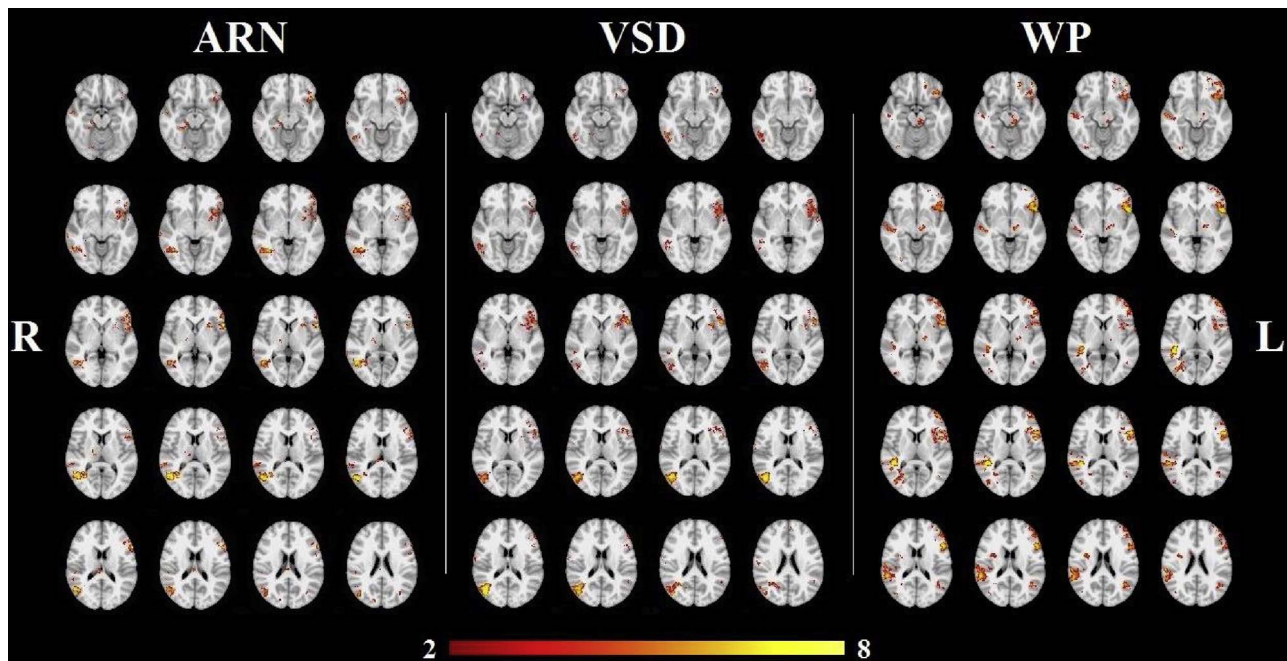
Fig. 4. The areas where there were significant lateralized differences in the amplitude of hemodynamic responses to language stimuli, in ARN, VSD and WP tasks (FDR correction, p < 0.05, and cluster extension of 25 voxels). Active voxels in the left hemisphere show L > R for brain activations; active voxels in the right hemisphere show R > L for brain activations. R: right; L: left; ARN: Auditory Response Naming; VSD: Visual Semantic Decision; WP: Word Production.

right hemisphere could also be associated with the higher demands for the integrations during processing [103], joint participation in performing a task [145], or a product of connections with their homologue areas in the left hemisphere [135]. There are some notions that co-activation of brain areas reflects a brain circuit devoted to the performance of the target function [62,101], especially in a complicated function such as word production. Altogether, we observed here that covert paradigms are ideal for localization of most brain areas involved in language [146].

4.5. Theories on neuroanatomy of language

There are theories on the collaboration of brain areas for language production, perception, and comprehension. The first theory defined a dorsal-ventral stream in the auditory system, originating from core auditory areas and ending in the areas of the frontal cortex, handling the processing of 'what' and 'where' streams [147]. Due to the lack of a consensus on this theory, the second theory tried to more clearly define these two pathways as the linkage between the non-primary co-chleotopic auditory fields of superior temporal cortex and some important regions in the inferior frontal lobe [148,149]; however, this theory only tracks the frequency spectra of the auditory signal and spatial information and did not explain the interaction between information within dorsal pathway [96]. Consequently, the third theory, going beyond these descriptions, proposed a functional neuroanatomical theory about speech processing in bilateral temporal lobes [150], which later devoted some processing to the motor cortex, known as auditory-motor integration, and is applicable to both language perception and production [132,151,152].

Based on this theory, the first stage of perception takes place in the bilateral superior temporal gyrus (STG). Then, information flows in two separate processing streams, which consist of a bilateral ventral stream for mapping sound onto meaning [81], as well as a bilateral dorsal stream to transfer sound to an articulatory-based representation [153]. The bi-directionality in the dorsal and ventral streams mediate the proper asymmetrical transformations of sound and meaning, and therefore both streams and both hemispheres take part in speech perception and production.

With the scientific progress in the field of brain imaging, another model of language processing based on "design perspective" has been proposed, which tries to explain language processing regarding its three functional components including Memory, Unification, and Control (MUC). In this recent theory, linguistic knowledge (Memory) stored in temporal cortex and angular gyrus in parietal cortex is the core element for combining lexical elements of language on their phonological and semantic levels (Unification). This is suggested to take place in BA 44, 45 and 47, in the frontal cortex. For the last function, the dorsolateral prefrontal cortex, anterior cingulate cortex and some parts of the parietal cortex which are typically engaged in attention play the central roles (Control) [3,85,154].

As a matter of fact, there are many theories trying to discover the secret of language network and engagement of the right hemisphere in it [155], but the biggest similarity among them is the truth that language function requires contribution of brain cortex, from frontal to parietal and temporal lobes, as well as subcortical structures such as thalamus, basal ganglia, cerebellum and midbrain structures [59,156–158]. Additionally, it has been proved that scientists should change their insight into relating a specific brain area to language production or comprehension, on their shared brain mechanisms [159]. Language, as a computational ability [160], should be regarded as a mixture of local circuits of processing steps based on different brain areas [161].

4.6. Strengths and limitations

This study tried to develop normative templates of the language function, applicable in clinics and especially in PSP, in a Persian population. Besides template construction, the study showed that the language should be considered to be dependent on a vast network of brain areas, and not only on single ones. Despite the large sample size of the study, its robust imaging and analysis methods, as well as the comprehensiveness of the selected language stimulus tasks, this study had some limitations.

We showed that our triple language tasks could significantly activate the essential brain areas responsible for language production, comprehension and semantic. Although our results are compatible with
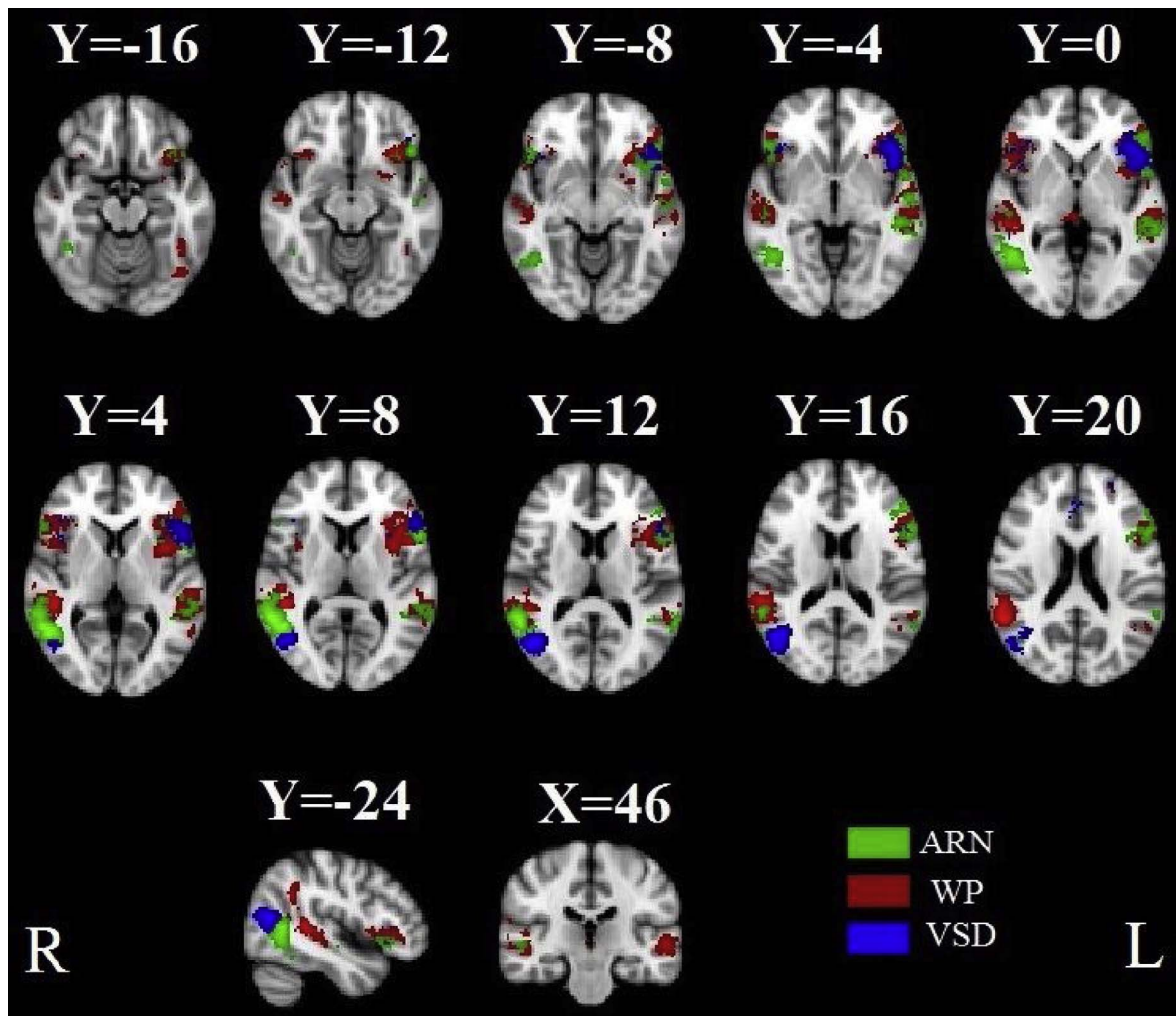
Fig. 5. The figure shows the amount of overlap between the language maps relevant to the three language tasks; each color represents one task. These overlays have been binarized for display purposes. R: right; L: left; ARN: Auditory Response Naming; VSD: Visual Semantic Decision; WP: Word Production.

many previous reports, it is speculated that due to the nature of fMRI, our language maps are task-dependent. In other words, a different language map might be obtained in a different task stimulus design. This question should be answered by comparing the behavioral language ability of those patients who have undergone PSP for the language function using our language templates, before and after their brain surgery.

Our results showed the activation of BA 44 and 45 to be left-lateralized in the three tasks, showing roles in language phonology and semantic; however, their right homologue areas were also active, which could be due to their engagement in executive function, attention or memory manipulation. On the contrary, there was a dominancy of the activation of BA 22 in the right. We suggest that the contribution of right BA 22 in language processing is an essential part of a bigger chain including left IFG, bilateral STG, and inferior parietal lobule. There are also reports that found the right hemisphere as the seat for phonological and semantic processing [155]. Due to little available information on the inter-hemispheric connections of brain areas in language processing, further studies are required to more clearly explain the exact role of the right hemisphere in the language function. Investigating the role of genetics in the development of language-related brain areas may also be beneficial [162].

Finally, we did not observe any gender influences on the language maps, despite the many reports that illustrated the language function to be bilateral in women and significantly left-lateralized in men

[163,164]. One reason for this discrepancy could be the variety of studies in their methods, such as their different populations, imaging, or the nature of their language tasks. Although there are reports on gender differences in the neural activity [165], it is speculated that there are minor gender effects in the language function.

Acknowledgments

References

[1] S.C. Levinson, R.D. Gray, Tools from evolutionary biology shed new light on the diversification of languages, Trends Cogn. Sci. 16 (2012) 167–173.
[2] M. Dunn, S.J. Greenhill, S.C. Levinson, R.D. Gray, Evolved structure of language shows lineage-specific trends in word-order universals, Nature 473 (2011) 79–82, http://dx.doi.org/10.1038/nature09923.
[3] P. Hagoort, On Broca, brain, and binding: a new framework, Trends Cogn. Sci. 9 (2005) 416–423.
[4] N.T. Sahin, S. Pinker, S.S. Cash, D. Schomer, E. Halgren, Sequential processing of lexical, grammatical, and phonological information within Broca's area, Science 326 (80-) (2009) 445–449.
[5] A.D. Friederici, W. Singer, Grounding language processing on basic neurophysiological principles, Trends Cogn. Sci. 19 (2015) 329–338.
[6] J.D. Griffiths, W.D. Marslen-Wilson, E.A. Stamatakis, L.K. Tyler, Functional organization of the neural language system: dorsal and ventral pathways are critical for syntax, Cereb. Cortex (2012) bhr386.

[7] P. Hagoort, Nodes and networks in the neural architecture for language: Broca's region and beyond, Curr. Opin. Neurobiol. 28 (2014) 136–141.

[8] N. Chomsky, Problems of projection, Lingua 130 (2013) 33–49.

[9] C.J. Price, A review and synthesis of the first 20 years of PET and fMRI studies of heard speech, spoken language and reading, Neuroimage 62 (2012) 816–847, http://dx.doi.org/10.1016/j.neuroimage.2012.04.062.

[10] M.-M. Mesulam, Principles of Behavioral and Cognitive Neurology, Oxford University Press, 2000.

[11] S.A.H. Batouli, N. Hasani, S. Gheisari, E. Behzad, M.A. Oghabian, Evaluation of the factors influencing brain language laterality in presurgical planning, Phys. Med. 32 (2016) 1201–1209, http://dx.doi.org/10.1016/j.ejmp.2016.06.008.

[12] M. Baciu, A. Juphard, E. Cousin, J.F. Le Bas, Evaluating fMRI methods for assessing hemispheric language dominance in healthy subjects, Eur. J. Radiol. 55 (2005) 209–218, http://dx.doi.org/10.1016/j.ejrad.2004.11.004.

[13] J.E. Desmond, S.H.A. Chen, Ethical issues in the clinical application of fMRI: factors affecting the validity and interpretation of activations, Brain Cogn. 50 (2002) 482–497.

[14] Y. Tie, L. Rigolo, I.H. Norton, R.Y. Huang, W. Wu, D. Orringer, S. Mukundan, A.J. Golby, Defining language networks from resting-state fMRI for surgical planning—a feasibility study, Hum. Brain Mapp. 35 (2014) 1018–1030.

[15] A.J. Steven, W.B. Altmeyer, Clinical vignette: functional MRI in preoperative assessment of neurosurgical patients, Neurographics 5 (2015) 128–132.

[16] S. Sunaert, Presurgical plan for tumor resectioning, J. Magn. Reson. Imaging 905 (2006) 887–905, http://dx.doi.org/10.1002/jmri.20582.

[17] J.R. Petrella, L.M. Shah, K.M. Harris, A.H. Friedman, T.M. George, J.H. Sampson, J.S. Pekala, J.T. Voyvodic, Preoperative functional MR imaging localization of language and motor areas: effect on therapeutic decision making in patients with potentially resectable brain tumors, Radiology 240 (2006) 793–802, http://dx.doi.org/10.1148/radiol.2403051153.

[18] Z. Yao, B. Hu, Y. Xie, P. Moore, J. Zheng, A review of structural and functional brain networks: small world and atlas, Brain Inform. 2 (2015) 45–52.

[19] P. Liang, L. Shi, N. Chen, Y. Luo, X. Wang, K. Liu, V.C.T. Mok, W.C.W. Chu, D. Wang, K. Li, Construction of brain atlases based on a multi-center MRI dataset of 2020 Chinese adults, Sci. Rep. 5 (2015).

[20] C.-M. Huang, S.-H. Lee, T. Hsiao, W.-C. Kuan, Y.-Y. Wai, H.-J. Ko, Y.-L. Wan, Y.-Y. Hsu, H.-L. Liu, Study-specific EPI template improves group analysis in functional MRI of young and old adults, J. Neurosci. Methods 189 (2010) 257–266.

[21] A. Mahdavi, S. Houshmand, M.A. Oghabian, M. Zarei, A. Mahdavi, M.H. Shoar, H. Ghanaati, Developing optimized fMRI protocol for clinical use: comparison of different language paradigms, J. Magn. Reson. Imaging 34 (2011) 413–419, http://dx.doi.org/10.1002/jmri.22604.

[22] J.C. Mazziotta, R. Woods, M. Iacoboni, N. Sicotte, K. Yaden, M. Tran, C. Bean, J. Kaplan, A.W. Toga, The myth of the normal, average human brain—the ICBM experience: (1) subject screening and eligibility, Neuroimage 44 (2009) 914–922, http://dx.doi.org/10.1016/j.neuroimage.2008.07.062.

[23] M.F. Folstein, S.E. Folstein, P.R. McHugh, "Mini-mental state". A practical method for grading the cognitive state of patients for the clinician, J. Psychiatr. Res. 12 (1975) 189–198 0022-3956(75)90026-6 [pii].

[24] R.C. Oldfield, The assessment and analysis of handedness: the Edinburgh inventory, Neuropsychologia 9 (1971) 97–113, http://dx.doi.org/10.1016/0028-3932(71)90067-4.

[25] Tehran University of Medical Sciences—statement on publication ethics, Arch. Iran. Med. 12 (2009).

[26] A. Mahdavi, H. Saberi, A. Rezvanizadeh, Functional imaging of Broca's area in native Persian speakers: an fMRI study, Iran. J. Radiol. 5 (2008) 215–220 (Accessed June 15, 2015), http://en.journals.sid.ir/ViewPaper.aspx?ID=128501.

[27] A. Mahdavi, S. Houshmand, M.A. Oghabian, M. Zarei, A. Mahdavi, M.H. Shoar, H. Ghanaati, Developing optimized fMRI protocol for clinical use: comparison of different language paradigms, J. Magn. Reson. Imaging 34 (2011) 413–419, http://dx.doi.org/10.1002/jmri.22604.

[28] A. Mahdavi, H. Saberi, S. Hooshmand, A. Rezvanizadeh, A. Lavasani, R. Nilipour, M. Zarei, M.A. Oghabian, Cortical representation of Persian word production: an fMRI study, Arch. Iran. Med. 13 (2010) 223–229 http://www.ncbi.nlm.nih.gov/pubmed/20433227.

[29] M. Fakhri, M.A. Oghabian, F. Vedaei, A. Zandieh, N. Masoom, G. Sharifi, M. Ghodsi, K. Firouznia, The Investigation of Functional Brain Lateralization by Transcranial Doppler Sonography 28 (2013), pp. 55–61.

[30] ASFNR, Language Functional MRI Paradigms, (ASFNR), Am. Soc. Funct. Neuroradiol. (2017). https://www.asfnr.org/.

[31] N. Pouratian, S.Y. Bookheimer, D.E. Rex, N.A. Martin, A.W. Toga, Utility of preoperative functional magnetic resonance imaging for identifying language cortices in patients with vascular malformations, J. Neurosurg. 97 (2002) 21–32, http://dx.doi.org/10.3171/jns.2002.97.1.0021.

[32] E. Niskanen, M. Könönen, V. Villberg, M. Nissi, P. Ranta-aho, L. Säisänen, P. Karjalainen, M. Äikiä, R. Kälviäinen, E. Mervaala, The effect of fMRI task combinations on determining the hemispheric dominance of language functions, Neuroradiology 54 (2012) 393–405.

[33] N.P. Brennan, K.K. Peck, A. Holodny, Language mapping using fMRI and direct cortical stimulation for brain tumor surgery: the good, the bad, and the questionable, Top. Magn. Reson. Imaging TMRI 25 (2016) 1.

[34] K.M. Welker, R.O. De Jesus, R.E. Watson, M.M. Machulda, C.R. Jack, Altered functional MR imaging language activation in elderly individuals with cerebral leukoaraiosis, Radiology 265 (2012) 222–232.

[35] M. Jenkinson, C.F. Beckmann, T.E.J. Behrens, M.W. Woolrich, S.M. Smith, FSL, Neuroimage 62 (2012) 782–790, http://dx.doi.org/10.1016/j.neuroimage.2011.09.015.

[36] M. Jenkinson, Fast, automated, N-dimensional phase-unwrapping algorithm, Magn. Reson. Med. 49 (2003) 193–197, http://dx.doi.org/10.1002/mrm.10354.

[37] M. Jenkinson, P. Bannister, M. Brady, S. Smith, Improved optimization for the robust and accurate linear registration and motion correction of brain images, Neuroimage 17 (2002) 825–841.

[38] M. Jenkinson, S. Smith, A global optimisation method for robust affine registration of brain images, Med. Image Anal. 5 (2001) 143–156.

[39] M. Jenkinson, M. Pechaud, S. Smith, {BET2: MR}-Based Estimation of Brain, Skull Scalp Surface, (2005).

[40] Y. Zhang, M. Brady, S. Smith, Segmentation of brain MR images through a hidden Markov random field model and the expectation-maximization algorithm, IEEE Trans. Med. Imaging 20 (2001) 45–57, http://dx.doi.org/10.1109/42.906424.

[41] A.J. Bell, T.J. Sejnowski, An information-maximization approach to blind separation and blind deconvolution, Neural Comput. 7 (1995) 1129–1159.

[42] J. Himberg, A. Hyvärinen, F. Esposito, Validating the independent components of neuroimaging time series via clustering and visualization, Neuroimage 22 (2004) 1214–1222, http://dx.doi.org/10.1016/j.neuroimage.2004.03.027.

[43] E.B. Erhardt, S. Rachakonda, E.J. Bedrick, E.A. Allen, T. Adali, V.D. Calhoun, Comparison of multi-subject ICA methods for analysis of fMRI data, Hum. Brain Mapp. 32 (2011) 2075–2095, http://dx.doi.org/10.1002/hbm.21170.

[44] V.D. Calhoun, T. Adali, G.D. Pearlson, J.J. Pekar, A method for making group inferences from functional MRI data using independent component analysis, Hum. Brain Mapp. 14 (2001) 140–151.

[45] Y. Tie, S. Whalen, R.O. Suarez, A.J. Golby, Group independent component analysis of language fMRI from word generation tasks, Neuroimage 42 (2008) 1214–1225, http://dx.doi.org/10.1016/j.neuroimage.2008.05.028.

[46] V.D. Calhoun, K.A. Kiehl, G.D. Pearlson, Modulation of temporally coherent brain networks estimated using ICA at rest and during cognitive tasks, Hum. Brain Mapp. 29 (2008) 828–838, http://dx.doi.org/10.1002/hbm.20581.

[47] J. Xu, S. Zhang, V.D. Calhoun, J. Monterosso, C.-S.R. Li, P.D. Worhunsky, M. Stevens, G.D. Pearlson, M.N. Potenza, Task-related concurrent but opposite modulations of overlapping functional networks as revealed by spatial ICA, Neuroimage 79 (2013) 62–71, http://dx.doi.org/10.1016/j.neuroimage.2013.04.038.

[48] N. Correa, T. Adali, V.D. Calhoun, Performance of blind source separation algorithms for fMRI analysis using a group ICA method, Magn. Reson. Imaging 25 (2007) 684–694, http://dx.doi.org/10.1016/j.mri.2006.10.017.

[49] V.D. Calhoun, T. Adali, V.B. McGinty, J.J. Pekar, T.D. Watson, G.D. Pearlson, fMRI activation in a visual-perception task: network of areas detected using the general linear model and independent components analysis, Neuroimage 14 (2001) 1080–1088, http://dx.doi.org/10.1006/nimg.2001.0921.

[50] S. Ma, N.M. Correa, X.-L. Li, T. Eichele, V.D. Calhoun, T. Adalı, Automatic identification of functional clusters in FMRI data using spatial dependence, IEEE Trans. Biomed. Eng. 58 (2011) 3406–3417, http://dx.doi.org/10.1109/TBME.2011.2167149.

[51] Y.-O. Li, T. Adali, V.D. Calhoun, Estimating the number of independent components for functional magnetic resonance imaging data, Hum. Brain Mapp. 28 (2007) 1251–1266, http://dx.doi.org/10.1002/hbm.20359.

[52] D. Il Kim, D.S. Manoach, D.H. Mathalon, J.A. Turner, M. Mannell, G.G. Brown, J.M. Ford, R.L. Gollub, T. White, C. Wible, A. Belger, H.J. Bockholt, V.P. Clark, J. Lauriello, D. O'Leary, B.A. Mueller, K.O. Lim, N. Andreasen, S.G. Potkin, V.D. Calhoun, Dysregulation of working memory and default-mode networks in schizophrenia using independent component analysis, an fBIRN and MCIC study, Hum. Brain Mapp. 30 (2009) 3795–3811, http://dx.doi.org/10.1002/hbm.20807.

[53] S. Zhang, C.R. Li, Functional networks for cognitive control in a stop signal task: independent component analysis, Hum. Brain Mapp. 33 (2012) 89–104, http://dx.doi.org/10.1002/hbm.21197.

[54] S.A. Meda, M.C. Stevens, B.S. Folley, V.D. Calhoun, G.D. Pearlson, Evidence for anomalous network connectivity during working memory encoding in schizophrenia: an ICA based analysis, PLoS One 4 (2009) e7911, , http://dx.doi.org/10.1371/journal.pone.0007911.

[55] Y. Grodzinsky, A. Santi, The battle for Broca's region, Trends Cogn. Sci. 12 (2008) 474–480, http://dx.doi.org/10.1016/j.tics.2008.09.001.

[56] D. Poeppel, G. Hickok, Towards a new functional anatomy of language, Cognition 92 (2004) 1–12, http://dx.doi.org/10.1016/j.cognition.2003.11.001.

[57] K. Amunts, K. Zilles, Architecture and organizational principles of Broca's region, Trends Cogn. Sci. 16 (2012) 418–426, http://dx.doi.org/10.1016/j.tics.2012.06.005.

[58] M.C. Stevens, V.D. Calhoun, K.A. Kiehl, Hemispheric differences in hemodynamics elicited by auditory oddball stimuli, Neuroimage 26 (2005) 782–792, http://dx.doi.org/10.1016/j.neuroimage.2005.02.044.

[59] P. Tremblay, A.S. Dick, Broca and Wernicke are dead, or moving past the classic model of language neurobiology, Brain Lang. 162 (2016) 60–71.

[60] D. Poeppel, K. Emmorey, G. Hickok, L. Pylkkänen, Towards a new neurobiology of language, J. Neurosci. 32 (2012) 14125–14131, http://dx.doi.org/10.1523/JNEUROSCI.3244-12.2012.

[61] J.R. Binder, The Wernicke area modern evidence and a reinterpretation, Neurology 85 (2015) 2170–2175.

[62] A. Ardila, B. Bernal, M. Rosselli, How localized are language brain areas? A review of Brodmann areas involvement in oral language, Arch. Clin. Neuropsychol. 31 (2016) 112–122.

[63] B.R. Buchsbaum, G. Hickok, C. Humphries, Role of left posterior superior temporal gyrus in phonological processing for speech perception and production, Cogn. Sci. 25 (2001) 663–678, http://dx.doi.org/10.1016/S0364-0213(01)00048-9.

[64] A.D. Friederici, The cortical language circuit: from auditory perception to sentence comprehension, Trends Cogn. Sci. 16 (2012) 262–268.

[65] I. DeWitt, J.P. Rauschecker, Wernicke's area revisited: parallel streams and word processing, Brain Lang. 127 (2013) 181–191, http://dx.doi.org/10.1016/j.bandl.2013.09.014.

[66] A.D. Friederici, Towards a neural basis of auditory sentence processing, Trends Cogn. Sci. 6 (2002) 78–84.

[67] M. Jung-Beeman, Bilateral brain processes for comprehending natural language, Trends Cogn. Sci. 9 (2005) 512–518, http://dx.doi.org/10.1016/j.tics.2005.09.009.

[68] S. Tune, M. Schlesewsky, A. Nagels, S.L. Small, I. Bornkessel-Schlesewsky, Sentence understanding depends on contextual use of semantic and real world knowledge, Neuroimage (2016).

[69] A.D. Friederici, S.-A. Rüschemeyer, A. Hahne, C.J. Fiebach, The role of left inferior frontal and superior temporal cortex in sentence comprehension: localizing syntactic and semantic processes, Cereb. Cortex 13 (2003) 170–177, http://dx.doi.org/10.1093/cercor/13.2.170.

[70] J. Obleser, S.A. Kotz, Expectancy constraints in degraded speech modulate the language comprehension network, Cereb. Cortex 20 (2010) 633–640, http://dx.doi.org/10.1093/cercor/bhp128.

[71] M.J. Schlosser, N. Aoyagi, R.K. Fulbright, J.C. Gore, G. McCarthy, Functional MRI studies of auditory comprehension, Hum. Brain Mapp. 6 (1998) 1–13.

[72] A.L. Giraud, C. Kell, C. Thierfelder, P. Sterzer, M.O. Russ, C. Preibisch, A. Kleinschmidt, Contributions of sensory input, auditory search and verbal comprehension to cortical activity during speech processing, Cereb. Cortex 14 (2004) 247–255.

[73] A.D. Friederici, The brain basis of language processing: from structure to function, Physiol. Rev. 91 (2011) 1357–1392, http://dx.doi.org/10.1152/physrev.00006.2011.

[74] Y.-S. Lee, P. Turkeltaub, R. Granger, R.D.S. Raizada, Categorical speech processing in Broca's area: an fMRI study using multivariate pattern-based analysis, J. Neurosci. 32 (2012) 3942–3948.

[75] C. Rogalsky, D. Almeida, J. Sprouse, G. Hickok, Sentence processing selectivity in Broca's area: evident for structure but not syntactic movement, Lang. Cogn. Neurosci. (2015) 1–13, http://dx.doi.org/10.1080/23273798.2015.1066831.

[76] E. Zaccarella, A.D. Friederici, Merge in the human brain: a sub-region based functional investigation in the left pars opercularis, Front. Psychol. 6 (2015).

[77] I. Bornkessel, S. Zysset, A.D. Friederici, D.Y. von Cramon, M. Schlesewsky, Who did what to whom? The neural basis of argument hierarchies during language comprehension, Neuroimage 26 (2005) 221–233.

[78] R.J. Zatorre, A. Evans, E. Meyer, Neural mechanisms underlying melodic perception and memory for pitch, J. Neurosci. 14 (1994) 1908–1919.

[79] F. Pulvermüller, L. Fadiga, Active perception: sensorimotor circuits as a cortical basis for language, Nat. Rev. Neurosci. 11 (2010) 351–360, http://dx.doi.org/10.1038/nrn2811.

[80] G. Hickok, J. Houde, F. Rong, Sensorimotor integration in speech processing: computational basis and neural organization, Neuron 69 (2011) 407–422.

[81] G. Hickok, D. Poeppel, Dorsal and ventral streams: a framework for understanding aspects of the functional anatomy of language, Cognition 92 (2004) 67–99.

[82] D. Poeppel, P.J. Monahan, Feedforward and feedback in speech perception: revisiting analysis by synthesis, Lang. Cogn. Process. 26 (2011) 935–951, http://dx.doi.org/10.1080/01690965.2010.493301.

[83] A. Seydell-Greenwald, A.S. Greenberg, J.P. Rauschecker, Are you listening? Brain activation associated with sustained nonspatial auditory attention in the presence and absence of stimulation, Hum. Brain Mapp. 35 (2014) 2233–2252.

[84] B. Plakke, L.M. Romanski, Neural circuits in auditory and audiovisual memory, Brain Res. 1640 (2016) 278–288.

[85] P. Hagoort, MUC (memory, unification, control): a model on the neurobiology of language beyond single word processing, Neurobiol. Lang. (2016) 339–347 Elsevier.

[86] F. Vergani, L. Lacerda, J. Martino, J. Attems, C. Morris, P. Mitchell, M.T. de Schotten, F. Dell'Acqua, White matter connections of the supplementary motor area in humans, J. Neurol. Neurosurg. Psychiatry (2014), http://dx.doi.org/10.1136/jnnp-2013-307492 jnnp–2013–307492.

[87] M. Catani, F. Dell'Acqua, F. Vergani, F. Malik, H. Hodge, P. Roy, R. Valabregue, M. Thiebaut de Schotten, Short frontal lobe connections of the human brain, Cortex 48 (2012) 273–291, http://dx.doi.org/10.1016/j.cortex.2011.12.001.

[88] S.C. Herholz, A.R. Halpern, R.J. Zatorre, Neuronal correlates of perception, imagery, and memory for familiar tunes, J. Cogn. Neurosci. 24 (2012) 1382–1397, http://dx.doi.org/10.1162/jocn_a_00216.

[89] P.E.G. Bestelmeyer, P. Maurage, J. Rouger, M. Latinus, P. Belin, Adaptation to vocal expressions reveals multistep perception of auditory emotion, J. Neurosci. 34 (2014) 8098–8105, http://dx.doi.org/10.1523/JNEUROSCI.4820-13.2014.

[90] S.K. Scott, S. Rosen, L. Wickham, R.J.S. Wise, A positron emission tomography study of the neural basis of informational and energetic masking effects in speech perception, J. Acoust. Soc. Am. 115 (2004) 813–821, http://dx.doi.org/10.1121/1.1639336.

[91] R. Jardri, D. Pins, M. Bubrovszky, P. Despretz, J.P. Pruvo, M. Steinling, P. Thomas, Self awareness and speech processing: an fMRI study, Neuroimage 35 (2007) 1645–1653, http://dx.doi.org/10.1016/j.neuroimage.2007.02.002.

[92] J.E. Peelle, V. Troiani, A. Wingfield, M. Grossman, Neural processing during older adults' comprehension of spoken sentences: age differences in resource allocation and connectivity, Cereb. Cortex 20 (2010) 773–782, http://dx.doi.org/10.1093/cercor/bhp142.

[93] H.S. Gauvin, W. De Baene, M. Brass, R.J. Hartsuiker, Conflict monitoring in speech processing: an fMRI study of error detection in speech production and perception, Neuroimage 126 (2016) 96–105.

[94] P. Tremblay, S.L. Small, From language comprehension to action understanding

[95] R.H. Desai, J.R. Binder, L.L. Conant, M.S. Seidenberg, Activation of sensory-motor areas in sentence comprehension, Cereb. Cortex 20 (2010) 468–478, http://dx.doi.org/10.1093/cercor/bhp115.

[96] R.J. Zatorre, M. Bouffard, P. Ahad, P. Belin, Where is "where" in the human auditory cortex? Nat. Neurosci. 5 (2002) 905–909, http://dx.doi.org/10.1038/nn904.

[97] N. Gaab, C. Gaser, T. Zaehle, L. Jancke, G. Schlaug, Functional anatomy of pitch memory—an fMRI study with sparse temporal sampling, Neuroimage 19 (2003) 1417–1426, http://dx.doi.org/10.1016/S1053-8119(03)00224-6.

[98] M. Petrides, B. Alivisatos, E. Meyer, A.C. Evans, Functional activation of the human frontal cortex during the performance of verbal working memory tasks, Neurobiology 90 (1993) 878–882, http://dx.doi.org/10.1073/pnas.90.3.878.

[99] J.R. Binder, R.H. Desai, W.W. Graves, L.L. Conant, Where is the semantic system? A critical review and meta-analysis of 120 functional neuroimaging studies, Cereb. Cortex 19 (2009) 2767–2796, http://dx.doi.org/10.1093/cercor/bhp055.

[100] E.F. Lau, C. Phillips, D. Poeppel, A cortical network for semantics: (de)constructing the N400, Nat. Rev. Neurosci. 9 (2008) 920–933, http://dx.doi.org/10.1038/Nrn2532.

[101] B. Bernal, A. Ardila, M. Rosselli, Broca's area network in language function: a pooling-data connectivity study, Front. Psychol. 6 (2015) 687.

[102] G. Josse, P.-Y. Hervé, F. Crivello, B. Mazoyer, N. Tzourio-Mazoyer, Hemispheric specialization for language: brain volume matters, Brain Res. 1068 (2006) 184–193.

[103] S. Bookheimer, Functional MRT of language: new approaches to understanding the cortical organization of semantic processing, Annu. Rev. Neurosci. 25 (2002) 151–188, http://dx.doi.org/10.1146/annurev.neuro.25.112701.142946.

[104] F. Pulvermüller, F. Kherif, O. Hauk, B. Mohr, I. Nimmo-Smith, Distributed cell assemblies for general lexical and category-specific semantic processing as revealed by fMRI cluster analysis, Hum. Brain Mapp. 30 (2009) 3837–3850.

[105] R. Cabeza, L. Nyberg, 00JoCN_ImaCogII.pdf, J. Cogn. Neurosci. 12 (2000) 1–47.

[106] E. Musz, S.L. Thompson-Schill, Tracking competition and cognitive control during language comprehension with multi-voxel pattern analysis, Brain Lang. 165 (2017) 21–32, http://dx.doi.org/10.1016/j.bandl.2016.11.002.

[107] S.L. Thompson-Schill, M. D'Esposito, G.K. Aguirre, M.J. Farah, Role of left inferior prefrontal cortex in retrieval of semantic knowledge: a reevaluation, Proc. Natl. Acad. Sci. U. S. A. 94 (1997) 14792–14797, http://dx.doi.org/10.1073/pnas.94.26.14792.

[108] J.R. Booth, D.D. Burman, J.R. Meyer, Z. Lei, J. Choy, D.R. Gitelman, T.B. Parrish, M.M. Mesulam, Modality-specific and-independent developmental differences in the neural substrate for lexical processing, J. Neurolinguist. 16 (2003) 383–405.

[109] R. Tomasello, M. Garagnani, T. Wennekers, F. Pulvermüller, Brain connections of words, perceptions and actions: a neurobiological model of spatio-temporal semantic activation in the human cortex, Neuropsychologia (2016).

[110] G.E. Rice, M.A.L. Ralph, P. Hoffman, The roles of left versus right anterior temporal lobes in conceptual knowledge: an ALE meta-analysis of 97 functional neuroimaging studies, Cereb. Cortex (2015) bhv024.

[111] D. Hassabis, D. Kumaran, E.A. Maguire, Using imagination to understand the neural basis of episodic memory, J. Neurosci. 27 (2007) 14365–14374, http://dx.doi.org/10.1523/jneurosci.4549-07.2007.

[112] Y. Kobayashi, D.G. Amaral, Macaque monkey retrosplenial cortex: II. Cortical afferents, J. Comp. Neurol. 466 (2003) 48–79, http://dx.doi.org/10.1002/cne.10883.

[113] Y. Kobayashi, D.G. Amaral, Macaque monkey retrosplenial cortex: III. Cortical efferents, J. Comp. Neurol. 502 (2007) 810–833.

[114] R.A. Epstein, W.E. Parker, A.M. Feiler, Where am i now? Distinct roles for parahippocampal and retrosplenial cortices in place recognition, J. Neurosci. 27 (2007) 6141–6149, http://dx.doi.org/10.1523/JNEUROSCI.0799-07.2007.

[115] J.L. Vincent, A.Z. Snyder, M.D. Fox, B.J. Shannon, J.R. Andrews, M.E. Raichle, R.L. Buckner, Coherent spontaneous activity identifies a hippocampal-parietal memory network, J. Neurophysiol. 96 (2006) 3517–3531.

[116] F.Å. Nielsen, D. Balslev, L.K. Hansen, Mining the posterior cingulate: segregation between memory and pain components, Neuroimage 27 (2005) 520–532.

[117] R. Leech, D.J. Sharp, The role of the posterior cingulate cortex in cognition and disease, Brain 137 (2014) 12–32.

[118] A.C. Schapiro, J.L. McClelland, S.R. Welbourne, T.T. Rogers, M.A.L. Ralph, Why bilateral damage is worse than unilateral damage to the brain, J. Cogn. Neurosci. 25 (2013) 2107–2123.

[119] J.S. Snowden, J.C. Thompson, D. Neary, Famous people knowledge and the right and left temporal lobes, Behav. Neurol. 25 (2012) 35–44, http://dx.doi.org/10.3233/BEN-2012-0347.

[120] G. Pobric, E. Jefferies, M.A.L. Ralph, Amodal semantic representations depend on both anterior temporal lobes: evidence from repetitive transcranial magnetic stimulation, Neuropsychologia 48 (2010) 1336–1342.

[121] R.L. Jackson, M.A.L. Ralph, G. Pobric, The timing of anterior temporal lobe involvement in semantic processing, J. Cogn. Neurosci. (2015).

[122] K. Patterson, P.J. Nestor, T.T. Rogers, Where do you know what you know? The representation of semantic knowledge in the human brain, Nat. Rev. Neurosci. 8 (2007) 976–987, http://dx.doi.org/10.1038/nrn2277.

[123] M.A. Lambon Ralph, K. Patterson, Generalization and differentiation in semantic memory, Ann. N. Y. Acad. Sci. 1124 (2008) 61–76, http://dx.doi.org/10.1196/annals.1440.006.

[124] K. Amunts, M. Lenzen, A.D. Friederici, A. Schleicher, P. Morosan, N. Palomero-Gallagher, K. Zilles, Broca's region: novel organizational principles and multiple receptor mapping, PLoS Biol. 8 (2010), http://dx.doi.org/10.1371/journal.pbio.

1000489.

[125] A. Mahdavi, H. Saberi, A.R. Rezvanizadeh, A. Lavasani MSc, R. Nilipour, M.A. Oghabian, H. Ghanaati, Functional imaging of Broca's area in native Persian speakers: an fMRI study, Iran. J. Radiol. 6 (2008).

[126] C.J. Price, J.T. Crinion, M. MacSweeney, A generative model of speech production in Broca's and Wernicke's areas, Front. Psychol. 2 (2011), http://dx.doi.org/10.3389/fpsyg.2011.00237.

[127] S. Heim, S.B. Eickhoff, K. Amunts, Specialisation in Broca's region for semantic, phonological, and syntactic fluency? Neuroimage 40 (2008) 1362–1368, http://dx.doi.org/10.1016/j.neuroimage.2008.01.009.

[128] A. Flinker, A. Korzeniewska, A.Y. Shestyuk, P.J. Franaszczuk, N.F. Dronkers, R.T. Knight, N.E. Crone, Redefining the role of Broca's area in speech, Proc. Natl. Acad. Sci. 112 (2015) 2871–2875.

[129] N.E. Neef, C. Bütfering, A. Anwander, A.D. Friederici, W. Paulus, M. Sommer, Left posterior-dorsal area 44 couples with parietal areas to promote speech fluency, while right area 44 activity promotes the stopping of motor responses, Neuroimage 142 (2016) 628–644, http://dx.doi.org/10.1016/j.neuroimage.2016.08.030.

[130] S.K. Scott, Identification of a pathway for intelligible speech in the left temporal lobe, Brain 123 (2000) 2400–2406, http://dx.doi.org/10.1093/brain/123.12.2400.

[131] Levelt W. J.M, A. Roelofs, A.S. Meyer, A theory of lexical access in speech production, Behav. Brain Sci. 22 (1999) 1–75.

[132] K. Okada, G. Hickok, Left posterior auditory-related cortices participate both in speech perception and speech production: neural overlap revealed by fMRI, Brain Lang. 98 (2006) 112–117.

[133] R. Leech, L.L. Holt, J.T. Devlin, F. Dick, Expertise with artificial nonspeech sounds recruits speech–sensitive cortical regions, J. Neurosci. 29 (2009) 5234–5239, http://dx.doi.org/10.1523/JNEUROSCI.5758-08.2009.

[134] F.M. Richardson, M.L. Seghier, A.P. Leff, M.S.C. Thomas, C.J. Price, Multiple routes from occipital to temporal cortices during reading, J. Neurosci. 31 (2011) 8239–8247, http://dx.doi.org/10.1523/JNEUROSCI.6519-10.2011.

[135] D.R. Gitelman, A.C. Nobre, S. Sonty, T.B. Parrish, M.-M. Mesulam, Language network specializations: an analysis with parallel task designs and functional magnetic resonance imaging, Neuroimage 26 (2005) 975–985.

[136] M.-A. Tagamets, J.M. Novick, M.L. Chalmers, R.B. Friedman, A parametric approach to orthographic processing in the brain: an fMRI study, J. Cogn. Neurosci. 12 (2000) 281–297, http://dx.doi.org/10.1162/089892900562101.

[137] S.L. Rossell, C.J. Price, A.C. Nobre, The anatomy and time course of semantic priming investigated by fMRI and ERPs, Neuropsychologia 41 (2003) 550–564.

[138] K.B. McDermott, S.E. Petersen, J.M. Watson, J.G. Ojemann, A procedure for identifying regions preferentially activated by attention to semantic and phonological relations using functional magnetic resonance imaging, Neuropsychologia 41 (2003) 293–303, http://dx.doi.org/10.1016/S0028-3932(02)00162-8.

[139] M.G. Peeva, F.H. Guenther, J.A. Tourville, A. Nieto-Castanon, J.-L. Anton, B. Nazarian, F.-X. Alario, Distinct representations of phonemes, syllables, and supra-syllabic sequences in the speech production network, Neuroimage 50 (2010) 626–638.

[140] N.F. Ramsey, I.E. Sommer, G.J. Rutten, R.S. Kahn, Combined analysis of language tasks in fMRI improves assessment of hemispheric dominance for language functions in individual subjects, Neuroimage 13 (2001) 719–733, http://dx.doi.org/10.1006/nimg.2000.0722.

[141] S. Heim, B. Opitz, K. Müller, A.D. Friederici, Phonological processing during language production: fMRI evidence for a shared production-comprehension network, Cogn. Brain Res. 16 (2003) 285–296, http://dx.doi.org/10.1016/S0926-6410(02)00284-7.

[142] L. Friedman, J.T. Kenny, A.L. Wise, D. Wu, T.A. Stuve, D.A. Miller, J.A. Jesberger, J.S. Lewin, Brain activation during silent word generation evaluated with functional MRI, Brain Lang. 64 (1998) 231–256.

[143] H.W.R. Powell, G.J.M. Parker, D.C. Alexander, M.R. Symms, P.A. Boulby, C.A.M. Wheeler-Kingshott, G.J. Barker, U. Noppeney, M.J. Koepp, J.S. Duncan, Hemispheric asymmetries in language-related pathways: a combined functional MRI and tractography study, Neuroimage 32 (2006) 388–399.

[144] M.L. Seghier, F. Lazeyras, A.J. Pegna, J.-M. Annoni, I. Zimine, E. Mayer, C.M. Michel, A. Khateb, Variability of fMRI activation during a phonological and semantic language task in healthy subjects, Hum. Brain Mapp. 23 (2004) 140–155,

[145] M. Wilke, T. Pieper, K. Lindner, T. Dushe, H. Holthausen, I. Krägeloh-Mann, Why one task is not enough: functional MRI for atypical language organization in two children, Eur. J. Paediatr. Neurol. 14 (2010) 474–478.

[146] S. Partovi, F. Konrad, S. Karimi, F. Rengier, J.K. Lyo, L. Zipp, E. Nennig, C. Stippich, Effects of covert and overt paradigms in clinical language fMRI, Acad. Radiol. 19 (2012) 518–525.

[147] J.P. Rauschecker, Cortical processing of complex sounds, Curr. Opin. Neurobiol. 8 (1998) 516–521, http://dx.doi.org/10.1016/S0959-4388(98)80040-8.

[148] J.H. Kaas, T. a Hackett, "What" and "where" processing in auditory cortex, Nat. Neurosci. 2 (1999) 1045–1047, http://dx.doi.org/10.1038/15967.

[149] L.M. Romanski, B. Tian, J. Fritz, M. Mishkin, P.S. Goldman-Rakic, J.P. Rauschecker, Dual streams of auditory afferents target multiple domains in the primate prefrontal cortex, Nat. Neurosci. 2 (1999) 1131–1136.

[150] G. Hickok, D. Poeppel, Towards a functional neuroanatomy of speech perception, Trends Cogn. Sci. 4 (2000) 131–138.

[151] J.H. Venezia, P. Fillmore, W. Matchin, A.L. Isenberg, G. Hickok, J. Fridriksson, Perception drives production across sensory modalities: a network for sensorimotor integration of visual speech, Neuroimage 126 (2016) 196–207.

[152] G. Hickok, B. Buchsbaum, C. Humphries, T. Muftuler, Auditory–motor interaction revealed by fMRI: speech, music, and working memory in area Spt, J. Cogn. Neurosci. 15 (2003) 673–682.

[153] G.B. Cogan, T. Thesen, C. Carlson, W. Doyle, O. Devinsky, B. Pesaran, Sensorymotor transformations for speech occur bilaterally, Nature 507 (2014) 94.

[154] P. Hagoort, MUC (memory, unification, control) and beyond, Front. Psychol. 4 (2013) 1–13, http://dx.doi.org/10.3389/fpsyg.2013.00416.

[155] M. Vigneau, V. Beaucousin, P.Y. Hervé, G. Jobard, L. Petit, F. Crivello, E. Mellet, L. Zago, B. Mazoyer, N. Tzourio-Mazoyer, What is right-hemisphere contribution to phonological, lexico-semantic, and sentence processing? Insights from a meta-analysis, Neuroimage 54 (2011) 577–593, http://dx.doi.org/10.1016/j.neuroimage.2010.07.036.

[156] B. Crosson, Thalamic mechanisms in language: a reconsideration based on recent findings and concepts, Brain Lang. 126 (2013) 73–88, http://dx.doi.org/10.1016/j.bandl.2012.06.011.

[157] A.A. Bohsali, W. Triplett, A. Sudhyadhom, J.M. Gullett, K. McGregor, D.B. FitzGerald, T. Mareci, K. White, B. Crosson, Broca's area—thalamic connectivity, Brain Lang. 141 (2015) 80–88, http://dx.doi.org/10.1016/j.bandl.2014.12.001.

[158] P. Mariën, H. Ackermann, M. Adamaszek, C.H.S. Barwood, A. Beaton, J. Desmond, E. De Witte, A.J. Fawcett, I. Hertrich, M. Küper, M. Leggio, C. Marvel, M. Molinari, B.E. Murdoch, R.I. Nicolson, J.D. Schmahmann, C.J. Stoodley, M. Thürling, D. Timmann, E. Wouters, W. Ziegler, Consensus paper: language and the cerebellum: an ongoing enigma, Cerebellum 13 (2014) 386–410, http://dx.doi.org/10.1007/s12311-013-0540-5.

[159] J.R. Binder, The Wernicke area, Neurology 85 (2015) 2170–2175, http://dx.doi.org/10.1212/WNL.0000000000002219.

[160] D. Poeppel, The neuroanatomic and neurophysiological infrastructure for speech and language, Curr. Opin. Neurobiol. 28 (2014) 142–149.

[161] D. Poeppel, The maps problem and the mapping problem: two challenges for a cognitive neuroscience of speech and language, Cogn. Neuropsychol. 29 (2012) 34–55.

[162] P.S. Sachdev, T. Lee, W. Wen, D. Ames, A.H. Batouli, J. Bowden, H. Brodaty, E. Chong, J. Crawford, K. Kang, K. Mather, A. Lammel, M.J. Slavin, A. Thalamuthu, J. Trollor, M.J. Wright, The contribution of twins to the study of cognitive ageing and dementia: the older Australian twins study, Int. Rev. Psychiatry 25 (2013) 738–747, http://dx.doi.org/10.3109/09540261.2013.870137.

[163] K. Kansaku, S. Kitazawa, Imaging studies on sex differences in the lateralization of language, Neurosci. Res. 41 (2001) 333–337.

[164] E.M. Weiss, J.D. Ragland, C.M. Brensinger, W.B. Bilker, E.A. Deisenhammer, M. Delazer, Sex differences in clustering and switching in verbal fluency tasks, J. Int. Neuropsychol. Soc. 12 (2006) 502–509.

[165] M. Hirnstein, K. Hugdahl, M. Hausmann, How brain asymmetry relates to performance—a large-scale dichotic listening study, Front. Psychol. 4 (2013) 997, http://dx.doi.org/10.3389/fpsyg.2013.00997.