Neural correlates of healthy sustained vowel phonation tasks: A systematic review and meta-analysis of neuroimaging studies

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Abstract

Objective. This review of the methodology and results of studies involving a sustained vowel phonation tasks during functional Magnetic Resonance Imaging (fMRI) aims to contribute to the identification of brain regions involved in phonation for healthy subjects.

Data sources. This review was performed using the PubMed electronic database.

Review Methods. A review was conducted, according to PRISMA guidelines, between September and November 2020, using the following search term pairs: 'fMRI and Phonation' and 'fMRI and Voice'. Activation likelihood estimation (ALE) analysis was performed. A qualitative analysis was also performed to specify the frequency of activation of each region, as well as the various activation clusters within a single region.

Results. Seven studies were included and analyzed. Five of the seven studies were selected for the ALE meta-analysis which revealed significant convergent activation for only one cluster located in the left precentral gyrus (BA4). A qualitative review provides an overview of brain activation. Primary motor and premotor areas were the only activated areas in all studies included. Other regions previously considered to be implicated in phonation were often activated in sustained vowel phonation tasks. Additionally, areas generally associated with articulation or language also showed activation.

Conclusion. Methodological recommendations are suggested to isolate the phonatory component and reduce variability between future studies. Based on the qualitative analysis, this review does not support a distinction between regions more related to phonation and regions more related to articulation. Further research is required

seeking to isolate the vocal component and to improve insight into human brain network involved in phonation.

KEYWORDS

fMRI, sustained phonation, brain activation area, meta-analysis, voice

1. Introduction

Speech can be divided into two components: a phonatory component and an articulatory component [1]. The first one, phonation, is the voluntary production of a sound. It cannot be dissociated from respiration [2]. Indeed, phonation requires bilateral laryngeal muscle control to bring the vocal folds into an adduction position and involves the vibration of these folds thanks to the Bernoulli effect on the expiratory airflow. This phonatory mechanism relies on a precise and complex coordination with the respiratory system, the so-called pneumo-phonic coordination [3,4]. The voice is also involved in non-speech productions that are under less voluntary control such as screaming, crying or laughing. The second one, articulation, involves the articulator's placement (tongue, lips, cheeks, jaws, teeth, hard palate, velum, uvula and pharyngeal wall) in the correct position for the production of a phoneme (distinct units of sound in a specified language), and also involves the coarticulation of phonemes to produce speech (syllables, words, sentences). The phonatory and the articulatory components are therefore essential and linked.

Nervous damage, either central or peripheral, can result in specific difficulties in voicing, and therefore in the phonatory component of speech without impairing the articulatory component. Gaining greater understanding of the neural basis of normal phonation could provide a better insight into human brain adaptations following neurological voice disorders. Moreover, it could also be necessary to understand the effectivity of rehabilitation strategies offered to dysphonic patients as well as aid in taking clinical decisions concerning functional restoration of the phonation

For the phonatory component, the pneumo-phonic coordination is enabled by the action of different nerves for which the primary central nervous relays are the ambiguus nucleus and the nucleus of the solitary tract, in the brainstem for the motor phonation

part, and in the ventral horn of spinal cord for the respiration part [1,5]. The retroambiguus nucleus is also important for this coordination. Besides, the phonatory system depends on sensory inputs to ensure precise control and to be prepared for flight when necessary. Auditory and proprioceptive feedbacks are essential for this system to operate successfully [5,6,7]. Accordingly, there are many brain regions involved in phonation, located within the motor, the auditory and the somatosensory cortices [3].

Functional Magnetic Resonance Imaging (fMRI) to assess cortical and subcortical activity is increasingly being applied in studies involving speech production/perception physiology. In contrast to articulation and/or language activities, only few studies have shown interest in isolated phonation even though some pathologies only affect phonation without causing articulatory or language disorders. The review of Brown et al. [8] already addressed this issue of lack of interest in the neural activity for phonation, but, in their review, the authors have chosen to include vocal tasks at the syllable level, thus involving articulatory movements. In our opinion, however, sustained vowel phonation tasks represent an equally interesting option. Indeed, this task allows the recruitment of vocal fold vibration while minimizing the action of the speech articulation structures, and thus allows to focus on the phonatory system rather than on the other speech-related systems (i.e., articulation, speech, language). This is necessary to understand the functioning of the central nervous system involved in phonation.

To provide a synthesis of the precise coordinates of the brain and brainstem regions active during phonation, thereby providing a baseline for future voice-related neurophysiology research, we reviewed the methodology and results from fMRI studies on sustained vowel phonation. The aim of this study is therefore to review and

summarize the brain activation observed across different studies specifically for this task.

2. Methods

2.1 Literature search and study selection

A literature search was conducted by the first author between September and November 2020 according to PRISMA guidelines [9]. Studies using fMRI to assess voice-related brain activation were identified by searching in the PubMed electronic database with no limitation and using the following MeSH words [fMRI AND Phonation] and [fMRI AND Voice]. Then, reference lists were scanned for additional studies on the topic. All the papers found were in English. Inclusion and exclusion criteria are stated in Figure A1.

A total of 1363 articles were found. Eligibility assessment was performed by the first author with the possibility of requesting a second opinion from the co-authors. The PRISMA flow diagram [9] summarizes the study selection processes (Figure A2). Finally, eight articles met the inclusion and exclusion criteria, but one was further excluded because it contained data from a control group that was identical to the one presented in another study [10] by the same research team, which was already included in our selection. Seven studies [11,12,13,14,15,16,17] were included and analyzed, involving a total of 94 subjects.

2.2 Data collection

The following information was extracted from each included study: (1) sample size, (2) participant characteristics (gender, age, manual laterality), (3) description of the sustained vowel phonation task, and (4) description of the control task and any other

tasks used in the study (although these will not be analyzed in this review). These data have been summarized in Table A1.

Table A2 lists the following parameters and characteristics of the fMRI examinations: (1) scanner model, (2) temporal resolution (TR), (3) number of brain slices (linked to brain coverage), (4) spatial resolution, (5) choice to perform analysis in the whole brain or based on predefined regions of interest. We also included a summary of the essential aspects of the experimental paradigm, including: (1) number of events (task repetition), (2) presentation of instructions to the participants in the scanner (auditory or visual instructions, written or symbolic), (3) presence or absence of specific instructions regarding articulatory movements, (4) presence or absence of a recording of the patient's voice or of live voice monitoring in order to ensure that the tasks are carried out correctly, (5) presence or absence of auditory feedback information that the patient heard during phonation.

The Montreal Neurological Institute (MNI) or Talairach and Tournoux coordinates [18] of the regions mentioned in each article, for the difference between the sustained vowel phonation task and the rest condition ([sustained vowel phonation – rest (fixation)] contrast), were collected. Talairach and Tournoux coordinates were converted to MNI using the icbm2tal transformation method implemented in the BrainMap software [19] (brainmap.org/icbm2tal/; Research Imaging Institute, San Antonio, TX, USA). For each of the included studies, the original coordinates or the coordinates after conversion (in italics) are listed in Table A3.

To ensure correct reporting of the above information, data from the seven studies were extracted three times by the first author.

2.3 Activation likelihood estimation (ALE) analysis

Before proceeding, two studies [14,17] that have analyzed data based on regions of interest, were excluded from the meta-analysis. As these studies had already been focusing on regions previously cited in the literature, a bias may have been introduced by giving more weight to these regions.

MNI coordinates of the five other studies (listed in Table A3), have been entered into the GingerALE 3.0.2 tool based on the revised ALE algorithm for coordinate-based quantitative meta-analysis of neuroimaging results [20,21,22] that is available in the BrainMap database [23,24,25,26]. We performed a single dataset analysis using voxel-level inference. To exclude a random effect convergence, ALE scores were compared to a null distribution using a permutation test with 5000 permutations, to determine the statistical significance of the ALE results that assumes a random spatial association between studies. The resulting p-values were corrected at a threshold of an α set at 5%, using the voxel-level family-wise error (FWE) [27].

2.4 Qualitative analysis

To qualitatively investigate which regions are most frequently cited, we have reorganized the data into a table (Table A4) showing each region and the proportion of studies in which it is reported, showing bilateral, left-sided or right-sided activation. Two issues had to be considered. First, for the same reason as mentioned above, we included in this report only the same five studies as in the ALE meta-analysis [11,12,13,15,16]. Second, given the significant variability between studies in the naming of activated regions, each coordinate was identified in the Atlas of Mai et al. [28] and was renamed according to the terminology used in this atlas, to ensure that the same regions were correctly grouped for counting. In this atlas, the categorization of orbital and medial prefrontal cortices is based on the subdivision of Ongür et al. [29]. Some coordinates did not correspond to a specific region in the atlas; it was then

described as "Close to..." in italics to specify the region of which the coordinates were closest in proximity. The corresponding new labels of the regions are available in the last column of Table A3. It is necessary to note that the cerebellum is not included in this atlas, so the corresponding boxes are in darker grey in the table. Finally, in this new synthesis (Table A4), we arbitrarily chose to report only those regions that were cited in at least two different studies.

Within all identically named regions, we investigated whether there were multiple activation peaks. To this end, we performed distance measurements between coordinates on the same side. We decided to group under the same activation cluster, the closest coordinates within a maximum distance of 10 millimeters (mm). For the coordinates grouped in the same cluster, we calculated an average of the coordinates of the cluster. Some coordinates are not included in clusters because they are isolated more than 10mm from other activations; they are then reported independently. In a final step, bilaterality was examined. The distance between our clusters and isolated coordinates on the left were compared with those on the right. Activations that were closest and within 10mm, were considered bilateral. We report the distance in millimeters between the left and right activations.

The grouping of regions is presented in Table A4.

3. Results

3.1 Overview of included studies

As previously mentioned, we identify seven articles [11,12,13,14,15,16,17] requesting a sustained vowel phonation task from healthy subjects and reporting MRI results for this task compared to a resting condition. Tables A1 and A2 provide descriptive information on the basis of which these studies can be compared.

The number of subjects in the studies varied from 12 to 18 with a mean age ranging from 24.3 to 69.8 years. All subjects were right-handed. In four of the seven studies [11,12,13,14], subjects were asked to sustain /i:/ with durations varying from 4 to 10 seconds with a mean of 6 seconds (M = 4.94, SD = 2.12). In all studies, it was specified that this sustained phonation should be done at a comfortable pitch for the participant and/or without intonation variation. Six of the seven studies [11,13,14,15,16,17] investigated other tasks than sustained vowel phonation and resting, in their fMRI experimental design, but these are not analyzed in the present review because these conditions involved other parameters such as pitch variation, modified auditory feedback or articulatory movements. In the comparison condition, which was always a resting condition, participants were asked to focus on a word or a symbol in the center of the screen. Only Terumitsu et al. [17] did not provide this kind of detail.

Regarding the experimental designs across the studies, different parameters have been taken into consideration. First, the number of events (task repetition) in each condition was highly variable, ranging from 10 to 54. In four of the seven studies [12,13,15,16], the number of events was equivalent for the sustained phonation condition and for the resting condition. Second, concerning the instructions, Terumitsu et al. [17] did not provide any information about the format of the instructions. Two studies [14,15] chose to give auditory examples as instructions and five of the seven studies gave visual instructions (all studies except Loucks et al. [14]). One research team [16] did not specify the type of visual instruction, three teams [11,13,15] offered written instructions, and one team [12] offered visual symbolic instructions. Third, only three studies [11,13,15] specified the instructions given to participants to manage their articulatory movements necessary to produce the vowel. The first study [11] did not attempt to minimize these movements since the instruction was to close the mouth

between each production. The authors of the two other studies [13,15] asked participants to keep their mouth slightly open throughout the entire experiment in order to reduce the impact of articulatory movements on the results. Four, in five studies [12,13,14,15,16], the experimenters verified the correct execution of the task by recording the participant's voice or by live performance monitoring. Fifth, five studies [11,12,14,16,17] did not inform on the participant's ability to hear his or her own voice live during the experiment despite machine noise and the use of earplugs. In two studies [13,15], subjects could hear themselves live through an MRI compatible microphone and headphone.

3.2 ALE Meta-analysis

The studies of Loucks et al. [14] and Terumitsu et al. [17] were excluded from the meta-analysis because their analyses were based on predefined regions of interest. The set of five remaining studies contains data of a total of 64 subjects and 86 coordinates of activation foci for the [sustained vowel phonation – rest (fixation)] contrast. The ALE meta-analysis revealed significant convergent activation for only one cluster with an α set at 5% using a family-wise error correction at the voxel level. This cluster of 360mm³ from [-52, -14, 28] to [-44, -6, 38] centered at [-48.2, -9.9, 32.9] was located in the left precentral gyrus, in Brodmann's area 4 (BA4) (detected in 5/5 experiments). The peak MNI coordinates of this cluster were located at [-50, -8, 32] with an ALE value of 0.0176 (Z = 5.36, p = <.0001) (Figure A3).

3.3 Qualitative analysis

Given the insufficiently powered results reported by the ALE meta-analysis, it was deemed necessary to qualitatively analyze the activated regions. Table A4 summarizes this qualitative overview on 61 of the 86 coordinates reported in the five

studies, since those regions were mentioned in at least two different studies. These 61 coordinates correspond with 15 different regions in the atlas of Mai et al. [28].

In the frontal lobe, many areas appeared to be active during voicing. Concerning the precentral gyrus, all studies report activation in Brodmann's area 4 (BA4). Looking more in-depth at the MNI coordinates, three different peaks of activation in the primary motor cortex could be distinguished. These activations were bilateral with right-to-left correspondences within 5mm, although more studies reported activations on the left. Also in the precentral gyrus, Brodmann's area 6 (BA6) was cited in 4/5 studies with two peaks of activation in the premotor cortex, which was more frequently reported in the right part, with right-to-left correspondences further apart at around 9mm. Brodmann's area 43 was activated only on the left side in three studies and these three coordinates have been grouped under the same cluster. Concerning the inferior frontal gyrus, at the level of Brodmann's area 44, the opercular part showed activation on the right side in 2/5 studies for one cluster and the orbital part (OP47) revealed activation in 3/5 studies with no bilateralism under a distance of 10mm. Concerning the medial part of the superior frontal gyrus, and more precisely in the supplementary motor area (BA6), 2/5 studies showed activation with a bilateralism within 6mm.

In the temporal lobe, and more specifically in the primary auditory cortex area (BA42), activation was shown in the right planum temporale in 2/5 studies, and bilaterally in the anterior transverse temporal gyrus in 2/5 studies. In this latter gyrus, there was also activation in Brodmann's area 41 in 2/5 studies. Finally, two studies also reported activation in the left superior temporal gyrus (BA22).

Two studies out of five reported bilateral parietal operculum activation, in the supramarginal gyrus (BA40). In the same proportion of studies (2/5), the putamen and the thalamus, with at least one bilateral activation, also appeared to be of interest. The

insula was cited in 2/5 studies with two peaks of activation on the left side and one on the right side. Finally, the cerebellum was activated in 4/5 studies, with one bilateral cluster and two other peaks in the left part and in the right part.

These clusters and coordinates are shown in Figure A4.

4. Discussion

Only seven studies investigated brain activation during sustained vowel phonation and met the criteria of the present review. We decided to analyze the activated locations with an ALE meta-analysis and also qualitatively in order to increase our understanding of the central nervous system involved in phonation.

The following brain regions have shown activity during sustained vowel phonation in two or more of the five included studies: precentral gyrus (BA4, BA6, BA43), superior frontal gyrus (BA6), inferior frontal gyrus (BA44: opercular part, OP47: orbital part), planum temporale (BA42), superior temporal gyrus (BA22), anterior transverse temporal gyrus (BA41, BA42), parietal operculum (BA40), insula, putamen, thalamus and cerebellum. However, the only region that was activated in all five studies was the precentral gyrus in Broadmann's area 4 (BA4). This implies that the findings have been heterogeneous across these studies, even for a relatively simple task as sustaining a vowel. We will look more specifically at these regions in the light of Brown et al.'s review of the literature [8], which focused on the production of monosyllables, with consequently a more important articulatory component.

In their review of studies that used syllable production tasks, Brown et al. [8] proposed a model that distinguishes between "primary" regions for phonation and "secondary" regions that may have been more related to articulation. To identify these primary areas, the authors relied on one of their previous fMRI studies [30], which looked at

vocal folds adduction during sung vowels (which we considered as not sustained and which is why that study was not included in the present review) and glottal stop productions. According to these authors, the primary activation regions are the following: laryngeal motor cortex and associated premotor cortex, supplementary motor area, Heschl's gyrus (transverse temporal gyrus) and auditory association cortex of the posterior superior temporal gyrus (including the cortex of the dorsal Sylvian fissure at the parietal temporal junction) and lobule VI of the cerebellum.

In the present review, the first cluster in the precentral gyrus (BA4), found activated in 3/5 studies [11,15,16], corresponds to the coordinates reported as the dorsal laryngeal motor control area and more precisely, the ventromedial peak [2,8,30]. This corresponds with peak MNI coordinates (-50, -8, 32) as calculated with the ALE meta-analysis. Although it is predominantly found on the left side in this review and in some other studies (e.g. Loucks et al. [14]), this activation is reported by several authors [1,5,8] as being bilaterally activated. The second cluster of activation, found in the precentral gyrus (BA4), corresponds to the dorsolateral peak of the dorsal laryngeal motor control area reported by Brown et al. [8]. Considering these first two clusters, 3/5 studies [11,15,16] report activation in the ventromedial peak and 2/5 [12,13] report activation in the dorsolateral peak of the dorsal laryngeal motor control area. It is relevant to consider whether or not the precision of the fMRI acquisition allows in these studies to sufficiently clearly distinguish the two peaks. In addition, the region located in the precentral gyrus (BA43) and defined as the ventral laryngeal motor control area [2] was also activated only on the left side, in 3/5 studies of this review [11,15,16]. The location of the so-called "associated premotor areas" has never been clearly defined. Within the precentral gyrus, we found other areas of activation: Brodmann area 4 (MNI: -18, -30, 58 ; 18.5, -28.5, 62) and Brodmann area 6 (MNI: 60, -4, 36 ; 64, -5, 28 / 50, -

6.67, 38). This initial qualitative analysis of other activation foci in the motor and premotor cortices (view Table A4) may therefore serve as a preliminary basis for defining regions more precisely in future research. As in the review of Brown et al. [8], the qualitative analysis shows activation in the supplementary motor area (SMA), located in the medial part of the superior frontal gyrus, in 2/5 studies. The emergence of this area supports the hypothesis that the SMA not only plays a role in the motor planning of co-articulated speech, but also in the motor planning of one sustained vowel production [8]. Regarding the auditory regions, activations were found in 2/5 studies in the left superior temporal gyrus (BA22), in the right planum temporale (BA42) and bilaterally in the anterior transverse temporal gyrus (BA41 and BA42). The superior temporal gyrus (BA22) was shown to be particularly active for detecting a mismatch in the fundamental frequency between the expected/produced voice and its auditory and sensory versions [15]. Finally, the cerebellum also showed activation in four of five studies; these studies report activation in lobule VI and one study also reports activation in the Crus II. Given their surfacing after qualitative analysis, all these areas can be the “primary” neural activation network for voice [8].

Interestingly, in this review on “primary” (i.e., phonation-related) brain areas, areas considered “secondary” (i.e. articulation-related) by Brown et al. [8] also emerged as activated in a sustained vowel phonation task. In 2/5 studies, the frontal operculum (BA44), the thalamus, the insula and the putamen were also activated. These activations are reported by different studies included in this review and do not seem to be related to the degree of control of articulatory movements. Kryshtopava et al. [13] and Parkinson et al. [15] gave precise instructions to participants, asking them to keep their mouths slightly open during the entire experiment. The only articulatory movements required were those to place the tongue in the correct position for the

production of the vowels /i/ and /a/. It therefore seems unlikely that the activations recorded in these two studies (in the frontal operculum, insula, putamen, and thalamus) were due solely to the presence of single, minimal articulatory placement at the beginning of voice production. This review does not permit to support that these areas are more related to articulation and are not activated in sustained vowel phonation tasks. Their non-systematic activation in sustained vowel phonation tasks that are, *a priori*, quite similar and simple is surprising and does not allow us to conclude on their precise role. Brown et al. [8], in their review based on syllable production, already concluded that secondary areas would require more study. Moreover, as explained below, some methodological considerations are to be taken into account. The experimental design of the included studies varies considerably. This could also be the cause of some variability in these non-systematic activations.

Beyond the results of this review, the variability as well as limitations in experimental designs need to be discussed. First, various vowels were used across studies (for examples, view Table A1). Some studies [11,16] indicated that the chosen vowel minimizes the articulatory movements. Other authors reported choosing the vowel /i/ because it is the one that is most frequently used in other studies [11]. To minimize articulatory control and movement, it is necessary to choose the most neutral/central vowel in terms of mouth opening, labial rounding and lingual position. The vowel of choice would therefore be the schwa (as in Peck et al. [16]). Second, only Kryshtopava et al. [13] and Parkinson et al. [15] reported the precise speech instructions given to the participants. They instructed their participants to take an articulatory configuration already prior to the start of the vowel production and then to maintain this position during the whole experiment. No such instructions were reported in the other studies of this review, and therefore influences of articulation could not always be ruled out.

Third, to exclude language-based bias, the instructions should not be presented in written form nor oral form (for examples, view Table A1). Research on auditory voice perception [6] showed that similar areas of the auditory and the motor cortices are activated during perception and production of speech. Visual symbols are more adequate because their brain representation is the most distant from the functions being evaluated. Fourth, it is difficult to determine if and how subjects hear themselves during voice production in the MRI scanner, in which noise disturbs the air conduction-based hearing of speech sounds. A solution would therefore be to have an MRI-compatible headset with live voice feedback and ambient noise attenuation. If this equipment is not available, an alternative would be to add an audition-only condition where the patient hears his own pre-recorded voice performing the sustained vowel phonation task. This addition seems relevant since it will allow later on, to perform analyzes for the [phonation - audition] contrast, that allows to subtract the brain activation related to the hearing of one's voice and the scanner noises, from the activation related to phonation, and thus to more accurately isolate the voice production component.

Another limitation in the studies that were included in this review, and especially in the brain regions that were analyzed, is that in none of them the medulla oblongata, most caudal part of the brainstem was included, yet it is the first nervous relay of the voice [3]. The periaqueductal grey, located within the tegmentum of the midbrain, is a region known to play a role in emotional expression and may also be involved in speech production [31]. Moreover, although the number of slices reported in the included studies covers the cranial part of the brainstem, the midbrain, and also part of the pons, no study reports activation in these regions. Although there may be complications related to spatial resolution constraints or artifacts linked to respiratory movements

correlated to the task being studied, recommendations can be considered to optimize imaging of these regions [32]. Therefore, future scanning protocols should be adapted to also observe possible activation at the level of the brainstem.

We are also concerned about the need to report all the results in a common atlas in order to perform the qualitative analysis. Indeed, when we look at Table A3, we realize that some locations are different when renamed using the Mai et al. atlas [28] (e.g. “BA4: precentral gyrus” instead of “primary somatosensory cortex”). These differences make it difficult to qualitatively pool results from previous studies. This may be due to the reporting of very large regions with only the central coordinate of the area being mentioned. The cluster sizes of the reported areas in these five studies are highly variable. For the ALE meta-analysis and for the qualitative analysis, we also consider the question of normalization. Techniques for full normalization to a common space remain quite controversial, as it is difficult to ensure that registration to the common space preserves the topological variabilities, as well as the very fine details of the structure present in the original data. This may open discussions on this issue in the future with perhaps greater interest in studies where analyses are performed in the patient's native space.

Finally, it is important to discuss the task of interest in this review: sustained vowel phonation. This task has several advantages. From a practical point of view, it is well suited to MRI explorations because it requires very few movements and is easy for the participant to understand and perform. From a theoretical point of view, it allows to minimize the articulatory component of speech in benefit of the phonatory component. However, it should be reminded that it remains a rather unnatural task since we are rarely led to use our voice this way in everyday life.

5. Conclusion

The ALE meta-analysis revealed a single activation cluster, localized in the left precentral gyrus (BA4). This activation corresponds to the ventromedial peak of the dorsal laryngeal motor control area [2,8,30]. Although the ALE meta-analysis did not allow to identify the final set of active brain areas, the qualitative review provided an overview of the methodological aspects as well as brain activation coordinates of each of the included studies.

From this, it is recommended in future experimental designs, to reduce the articulatory component of the tasks as much as possible, to provide visual instructions via symbols during fMRI, and to specify the auditory feedback available to the participants. More specifically, to contrast different tasks in order to isolate the phonatory component more precisely, a correction for the brain activation due to auditory feedback is needed. Furthermore, brainstem analysis will also be required.

The qualitative analysis highlighted that primary motor and premotor areas are the only ones activated in all studies included. Other regions previously considered to be primary in phonation, however, are not always activated in sustained phonation tasks. In addition, areas generally associated with articulation or language also show activation and more investigation is required so that their role for phonation can be clarified. It is therefore difficult to make a distinction between regions more related to phonation and others more related to articulation, as all these regions show activation in some studies involving sustained vowel phonation, as well as a limited articulatory component. Further research seeking to isolate the vocal component is therefore essential in order to obtain a better insight into the human brain network for phonation and possibilities of human brain adaptation following neurological voice disorder and to better understand the role of each region. Subsequently, synthesis studies comparing brain activation observed through different tasks such as language tasks

(e.g., singing or producing words or sentences), speech tasks (e.g., phoneme coarticulation, syllable repetition), phonation tasks with a limited articulatory component (e.g. sustained phonation), non-speech vocal tasks (e.g. laughing, crying), and even breathing tasks would be very informative.

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Tables

Table A1 - *Description of studies included in the sustained phonation review*

	REFERENCE	POPULATION	GENDER	$\bar{X}$ AGE	MAN. LAT.	SUSTAINED PHONATION CONDITION	CONTROL CONDITION	OTHER CONDITION
1	Grabski et al., 2012	13 Ctrls	2F/11M	29 (21-44)	R	Vowel /i/ over 4, 5 or 6 sec. at comfortable pitch	Rest : fixation of the "pause" word	Articulatory movements (lip, tongue and jaw movements)
2	Kiyuna et al., 2020	12 Ctrls (+ 12 UVFP)	3F/9M	69,8 (53-79)	R	Vowel /i/ over 3 sec. at comfortable pitch	Rest : fixation of the "Ø" symbol	/
3	Kryshtopava et al., 2017	15 Ctrls	15F	24,3 (21-45)	R	Vowel /i/ over 10 sec. at comfortable pitch	Rest : fixation of a black cross	High pitch phonation, prolonged exhalation
4	Loucks et al., 2007	12 Ctrls	7F/5M	35 (SD:12)	R	Vowel /i/ over 4,5 sec. at comfortable pitch	Rest : fixation of an arrow	Repetition of the glottal syllable /ʔi/, exhalation task
5	Parkinson et al., 2012	12 Ctrls	5M/7F	28 (SD:11)	R	'ah' sound over 5 sec. at comfortable pitch	Rest : fixation of the "rest" word	Shifted-up auditory feedback, shifted-down auditory feedback
6	Peck et al., 2009	12 Ctrls	6F/6M	25,4 (SD:3,6)	R	'uh' sound over 4 sec. at comfortable pitch	Rest : fixation of a point	Low and high pitches phonation
7	Terumitsu et al., 2006	18 Ctrls	9F/9M	NA (18-43)	R	Japanese vowel /e/ over 3 sec. at comfortable pitch	Rest (no more information)	Tongue movements, phonation and tongue movements

Note. For the "**Population**", sometimes, the study included a pathologic group as well; this one is mentioned between brackets but is was not taken into account in the study. For the study 2, there was also a group of 12 patients with unilateral vocal fold paralysis (UVFP). In the "**Gender**" column, F is female and M is male."$\bar{X}$ **Age**" is the average age in years of the sample included in the analyses of this review. This column also includes the standard deviation (SD) or the range between the minimum and maximum ages. NA means "not available". "**Man. Lat.**" refers to the manual laterality; all subjects were right-handed. The fifth and the sixth columns describe the **sustained phonation (s.p.) condition** and the **control condition** of each study. Finally, the last column reports the **other conditions** proposed in the study, whose results are not discussed in this review.

Table A2 - *fMRI parameters description of studies included in the sustained phonation review*

	REFERENCE	SCANNER	TR (SEC.)	SLICES	SPATIAL RESOLUTION (MM)	WB OR ROI	EXPERIMENTAL DESIGN
1	Grabski et al., 2012	Bruker Medspec S300 3T	2.6	40 axial slices	3x3x3	WB	• 54 events of the **s.p.** condition, 18 events of the articulatory movements condition and 36 events of the **rest** condition in a pseudorandomized order • Written instructions • Initiate and end each movement with the mouth closed • No information on recording or monitoring of the subject voice • No information on self auditory feedback
2	Kiyuna et al., 2020	GE Discovery MR750 3T	2.7	42 axial slices	3x3x3	WB	• 36 events of each condition (**s.p.** and **rest**) in a pseudorandomized order • Symbolic visual instructions • No information on articulatory movements • Recording of the subject voice • No information on self-auditory feedback
3	Kryshtopava et al., 2017	Siemens Magnetom Trio 3T	2	40 axial slices	2x2x3	WB	• 12 events of each condition (comfortable **s.p.**, high pitch phonation, prolonged exhalation and **rest**) in a pseudorandomized order • Written instructions • Mouth always slightly open to minimize articulatory movement • Direct monitoring of the subject voice but no recording • Self auditory monitoring of voice during phonation with headphone
4	Loucks et al., 2007	NA	2.7	23 sagittal slices	3.5x3.5x6	ROI	• 45 events for the **s.p.** and syllable repetition conditions, 90 events for the exhalation condition and 120 trials for the **rest** condition in a randomized order • Auditory example as tasks instruction VS no acoustic cue for resting • No information on articulatory movements • Recording of the subject voice • No information on self-auditory feedback
5	Parkinson et al., 2012	Siemens Magnetom Trio 3T	3	43 slices	2x2x3	WB	• 48 events for each condition (**s.p.** no shift, shift-up, shift-down, **rest**) in a randomized order • Written instructions + acoustic cue for the s.p. task only

							• Mouth always slightly open to minimize articulatory movement • Recording of the subject voice • Self auditory monitoring of voice during phonation with headphone
6	Peck et al., 2009	GE Signa LX Scanner 3T	2	26 axial slices	1.875x1.875x4.5	WB	• 10 events for each condition (**comfortable s.p.**, low and high pitches, and **rest**) in a pseudorandomized order • Visual instructions but no information on the type • No information on articulatory movements • Direct monitoring of the subject voice but no recording • No information on self-auditory feedback
7	Terumitsu et al., 2006	GE Signa 3T	1 sec.	6 slices	3x3x5	ROI	• 18 events for the following conditions: **s.p.**, tongue movements and tongue movements and phonation conditions, and 27 events for **rest** condition in a sequential order • No information on instructions • Japanese vowel /e/ requires no tongue movements • No information on recording or monitoring of the subject voice • No information on self-auditory feedback

Note. The temporal resolution "**TR**" is measured in seconds. The three parameters of the "**Spatial resolution**" are given in millimetres; they correspond respectively to the x-axis, the y-axis and the thickness of the slice. The "**WB or ROI**" column specifies if the analyses were done in the whole brain (WB) or if the authors used predefined regions of interest (ROI). Finally, the "**Experimental design**" column summarizes the essential aspects of the experimental paradigm: • number of events in each condition of the study (see Table A1 for more details on conditions – "**s.p.**" means "sustained phonation"), • presentation of instructions (auditory or visual, written or symbolic), • presence or absence of specific instructions given to participants regarding articulatory movements, • presence or absence of a recording of the patient's voice or of live monitoring in order to ensure that the tasks are carried out correctly, and lastly, • presence or absence of auditory feedback information that the patient heard during phonation.

Table A3 - *MNI and/or Talairach coordinates*

REGIONS	MNI - Left			MNI - Right			CLUSTER SIZE (mm^3)		Renamed regions according to the Mai et al. atlas
	X	Y	Z	X	Y	Z	Left	Right	
1. Grabski et al. (2012)									
Primary motor cortex	-60	-4	18	52	-6	32			BA43: Precentral gyrus
Premotor cortex	-60	-4	36	54	-6	38			BA6: Precentral gyrus
Primary somatosensory cortex - L	-52	-8	32						BA4: Precentral gyrus
Primary somatosensory cortex - R				44	-8	30			*Close to BA4: Precentral gyrus*
Supplementary motor area	-4	-4	62	8	-4	60			BA6: Paracentral lobule
Transverse temporal gyrus	-42	-24	8	50	-16	6			BA41: Anterior transverse temporal gyrus
Superior temporal gyrus - R				52	-20	0			BA41: Anterior transverse temporal gyrus
Supramarginal gyrus - R				58	-26	24			BA43: Parietal operculum
Parietal operculum - L	-58	-6	10						BA43: Anterior central operculum
Parietal operculum - R				60	-4	6			BA42: Anterior transverse temporal gyrus
Insula - R				46	8	2	/	/	BA44: Frontal operculum
Cingulate cortex *(! No negative sign for X)* - L	10	14	34						BA32: Cingulate gyrus
Amygdala - R				26	-2	-8			Piriform cortex, temporal part
Putamen - L	-26	-8	-6						Amygdaloid island
Putamen - R				24	-4	-2			Putamen
Pallidum - R				22	-10	-4			Internal globus pallidus
Claustrum - R				32	-8	12			Putamen
Thalamus - L	-14	-20	0						Thalamus: basal inferior ventrolateral part
Thalamus - R				14	-18	4			Thalamus: posterior ventrolateral part
Cerebellum (declive)	-12	-64	-16	20	-60	-20			
Calcarine gyrus - L	18	-62	10						Anterior calcarine sulcus
2. Kiyuna et al. (2020)									
Precentral gyrus Postcentral gyrus Rolandic operculum Inferior frontal gyrus Transverse temporal gyrus Superior temporal gyrus	-44	-14	38	44	-12	38	6688	6982	BA4: Precentral gyrus

Insula									
Thalamus									
Caudate nucleus									
Putamen									
Amygdala									
Medial frontal gyrus - L/R	-6	-2	68				972		BA6: Superior frontal gyrus, medial part
Pre/Postcentral gyrus	-18	-30	58	22	-28	58	167	206	BA4: Precentral gyrus
Supramarginal gyrus - R				54	-38	30		18	BA40: Parietal operculum
Anterior cingulate cortex - L	-6	12	38				134		BA24: Cingulate gyrus
Hippocampus - L	-36	-12	-28				29		BA20: Fusiform gyrus
Amygdala - L									
Cerebellum - L	-22	-56	-30				905		
3. Kryshtopava et al. (2017)									
Precentral gyrus	*-45*	*-12*	*37*	*46*	*-4*	*37*	5298	7304	BA4: Precentral gyrus
Superior frontal gyrus	*-22*	*30*	*48*	*25*	*30*	*47*	713	756	BA8: Superior frontal gyrus, lateral part
Middle frontal gyrus - L	*-29*	*25*	*51*				1875		BA8: Middle frontal gyrus
Inferior frontal gyrus - L	*-51*	*49*	*-7*				135		*Close to OP47: Inferior frontal gyrus, orbital part (Öngür et al., 2003)*
Superior temporal gyrus - L	*-56*	*-35*	*15*				722		BA22: Superior temporal gyrus
Superior temporal gyrus - R				*63*	*-17*	*5*		7154	BA42: Planum temporale
Middle temporal gyrus (extends to parietal lobe)	*-42*	*-77*	*24*	*45*	*-69*	*18*	9782	639	BA37: Middle temporal gyrus
Cingulate gyrus - R				*29*	*-40*	*37*		596	BA7: Supramarginal gyrus
Posterior cingulate gyrus - L	*-2*	*-54*	*23*				5931		BA29/BA26: Isthmus of the cingulate gyrus
Posterior cingulate gyrus - R				*8*	*-54*	*21*			Isthmus of cingulate gyrus
Lingual gyrus - R				*41*	*-78*	*2*		17152	BA37: Inferior occipital gyrus
Thalamus (ventral posterior lateral nucleus) - R				*14*	*-8*	*16*		439	Thalamus: ventral anterior part
Cerebellum	*-29*	*-60*	*-26*	*3*	*-88*	*-34*	91	50	
4. Loucks et al. (2007)									
Ventrolateral cortex - L	*-62*	*-27*	*19*				6596		
Pre/Post central gyrus - L	*-46*	*-5*	*40*				1873		
Precentral gyrus - R				*40*	*-4*	*27*		664	
Supramarginal gyrus - R				*62*	*-38*	*45*		1001	
Midline supplementary motor area AND anterior cingulate cortex - L	*-4*	*-2*	*48*				886		

Inferior lingual gyrus - L	*43*	*-76*	*-9*				518		
Thalamus (ventral anterior, ventral lateral, ventral posteromedial, medial dorsal) - R				*11*	*-1*	*15*		1183	
Cerebellum - R				*9*	*-75*	*-12*		3902	
5. Parkinson et al. (2012)									
Supplementary motor area				1	0	66	/	/	BA6: Superior frontal gyrus, medial part
Precentral gyrus - L	-49	-7	32						*Close to BA4: Precentral Gyrus*
Precentral gyrus - R				50	-10	39			BA6: Precentral gyrus
				15	-29	66			BA4 : Precentral gyrus
Postcentral gyrus - L	-52	-7	21						BA43: Precentral Gyrus
Inferior frontal gyrus - L	-33	15	-10						OP47: Basal operculum (Öngür et al., 2003)
Inferior frontal gyrus - R				49	14	9			BA44: Inferior frontal gyrus, opercular part
Superior temporal gyrus - L	-61	-14	9						BA41: Anterior transverse temporal gyrus
	-61	-7	6						BA42: Anterior transverse temporal gyrus
	-59	-5	9						BA42 : Anterior transverse temporal gyrus
Superior temporal gyrus - R				61	-5	5			BA42: Anterior transverse temporal gyrus
				60	-12	-1			BA42: Planum temporale
Insula - L	-38	5	0						Insula
Insula - R				41	19	6			Precentral opercular area: Inferior frontal gyrus, orbital part (Öngür et al., 2003)
Putamen	-23	-4	6	22	3	6			Putamen
6. Peck et al. (2009)									
Inferior frontal gyrus - R				*32*	*36*	*0*		1127	OP47: Inferior frontal gyrus, orbital part (Öngür et al., 2003)
Precentral gyrus - L	*-48*	*-11*	*28*				2973		BA4: Precentral gyrus
Precentral gyrus - R				*64*	*-5*	*28*		3054	BA6: Precentral gyrus
Postcentral gyrus - L	*-55*	*-11*	*21*				2390		BA43: Precentral gyrus
Postcentral gyrus - R				*68*	*-6*	*16*		1725	*Close to BA1: Precentral gyrus*
Middle frontal gyrus - R				*40*	*54*	*-3*		790	OP47: Inferior frontal gyrus, orbital part (Öngür et al., 2003)
Superior temporal gyrus - L	*-58*	*-39*	*9*				2364		BA22: Superior temporal gyrus
Superior temporal gyrus - R				*51*	*-39*	*7*		2983	BA21 : Middle temporal gyrus
Inferior parietal lobe - L	*-48*	*-38*	*29*				692		BA40: Parietal operculum
Inferior parietal lobe - R				*47*	*-31*	*27*		261	Parietal operculum

Supramarginal gyrus	*-46*	*-36*	*34*	*45*	*-38*	*34*	332	116	BA40: Parietal operculum
Posterior cingulate	*-17*	*-68*	*14*	*11*	*-66*	*13*	178	265	BA17: Striate area
Insula	*-30*	*0*	*16*	*41*	*-2*	*15*	1989	336	Compact insular claustrum/Insula
Cerebellum (lobule VI)	*-21*	*-64*	*-21*	*33*	*-58*	*-23*	741	133	
7. Terumitsu et al. (2006)									
Primary motor cortex - L (superior cluster)	-40	-19	42				1035		
Primary motor cortex - L (inferior cluster)	-56	-3	21				450		
Primary motor cortex - R				51	-11	38		1350	

Note. Coordinates after conversion from Talairach to MNI are in italics (**3:** Kryshtopava et al., 2017; **4:** Loucks et al., 2007; **6:** Peck et al., 2009). The last column reports the renamed labels of each region according to the atlas of Mai et al. [28]. Some coordinates do not correspond to a specific region in the atlas; it was then written "Close to..." in italics to specify the region whose coordinates are the closest. The cerebellum is not included in the atlas, so the corresponding boxes are in darker grey. All studies were random effect studies, corrected for multiple comparisons (false discovery rate (qFDR), family wise error rate (FWE) or minimum cluster extend threshold).

Table A4 - *Qualitative analysis*

I		II						III						IV
REGIONS	**Prop.**	**Cluster L (10mm)**	**Prop.**	**Study ID**	**MNI coordinates** Left			**Cluster R (10mm)**	**Prop.**	**Study ID**	**MNI coordinates** Right			**Bilat. (mm)**
					X	Y	Z				X	Y	Z	
FRONTAL LOBE *(Figure A4: green)*														
BA4: Precentral gyrus	5/5	Cluster L1 (-49,67 ; -8,67 ; 30,67)	3/5	1	-52	-8	32	Cluster R1 (48 ; -7 ; 31)	1/5	1	52	-6	32	2,38
				5	*-49*	*-7*	*32*			1	*44*	*-8*	*30*	
				6	-48	-11	28							
		Cluster L2 (-44,5 ; -13 ; 37,5)	2/5	2	-44	-14	38	R2		2	44	-12	38	1,22
				3	-45	-12	37							
		L3		2	-18	-30	58	Cluster R3 (18,5 ; -28,5 ; 62)	2/5	2	22	-28	58	4,3
										5	15	-29	66	
BA6: Precentral gyrus	4/5	L1		1	-60	-4	36	R1		6	64	-5	28	9
								Cluster R2 (50 ; -6,67 ; 38)	3/5	3	46	-4	37	
										5	50	-10	39	
										1	54	-6	38	
BA43: Precentral gyrus	3/5	Cluster L1 (-55,67 ; -7,33 ; 20)	3/5	1	-60	-4	18							
				5	-52	-7	21							
				6	-55	-11	21							
BA6: Superior frontal gyrus, medial part	2/5	L1		2	-6	-2	68	R1		5	1	0	66	5,74
BA44: Frontal operculum/Inferior frontal gyrus, opercular part	2/5							Cluster R1 (47,5 ; 11 ; 5,5)	2/5	1	46	8	2	
										5	49	14	9	
OP47: Basal operculum/Inferior frontal gyrus, orbital part (Öngür et al., 2003)	3/5	L1		5	-33	15	-10							
		L2		3	*-51*	*49*	*-7*							
								R3		6	32	36	0	
								R4		6	40	54	-3	
TEMPORAL LOBE *(Figure A4: red)*														
BA42: Planum temporale	2/5							Cluster R1 (61,5 ; -14,5 ; 2)	2/5	3	63	-17	5	
										5	60	-12	-1	

BA22: Superior temporal gyrus	2/5	Cluster L1 (-57 ; -37 ; 12)	2/5	3	-56	-35	15							
				6	-58	-39	9							
BA41: Anterior transverse temporal gyrus	2/5	L1		5	-61	-14	9							
		L2		1	-42	-24	8							
								Cluster R3 (51 ; -18 ; 3)	1/5	1	50	-16	6	
										1	52	-20	0	
BA42: Anterior transverse temporal gyrus	2/5	Cluster L1 (-60 ; -6 ; 7,5)	1/5	5	-61	-7	6	Cluster R1 (60,5 ; -4,5 ; 5,5)	2/5	5	61	-5	5	2,55
				5	-59	-5	9			1	60	-4	6	
PARIETAL LOBE *(Figure A4: dark blue)*														
BA40: Parietal operculum	2/5	Cluster L1 (-47 ; -37 ; 31,5)	1/5	6	-48	-38	29	Cluster R1 (49,5 ; -38 ; 32)	2/5	2	54	-38	30	2,74
				6	-46	-36	34			6	45	-38	34	
								R2		6	47	-31	27	
INSULA *(Figure A4: purple)*														
Insula/Compact Insular claustrum	2/5	L1		6	-30	0	16							
		L2		5	-38	5	0							
								R3		6	41	-2	15	
PUTAMEN *(Figure A4: orange)*	2/5	L1		5	-23	-4	6	R1		5	22	3	6	7,07
								R2		1	24	-4	-2	
								R3		1	32	-8	12	
THALAMUS *(Figure A4 : light blue)*	2/5	L1		1	-14	-20	0	R1		1	14	-18	4	4,47
								R2		3	14	-8	16	
CEREBELLUM *(Figure A4: yellow)*	4/5	Cluster L1 (-25,5 ; -58 ; -28)	2/5	2	-22	-56	-30	R1		1	20	-60	-20	4,24
				3	-29	-60	-26							
		L2		1	-12	-64	-16							
		L3		6	-21	-64	-21							
								R4		3	3	-88	-34	
								R5		6	33	-58	-23	

Note. The table is organized in four vertically demarcated parts. The first part contains two first columns. The renamed regions according to the Mai et al. atlas [28] included in the first column are those cited in at least two different studies. The **"Prop."** column shows the number of studies among the 5 included studies that show activation in a specific region for the [sustained vowel phonation – rest (fixation)] contrast. The second part, which refers to the left side of the brain, contains four columns. The "**Cluster L (10mm)**" column lists the clusters of coordinates that are closest and within 10mm of each other, in an identically named region. The brackets under each cluster report the average coordinates of the cluster. Some coordinates are not clusters because they are isolated more than 10mm from other activations. The numbers in the column **"Study ID"** correspond to the number assigned to each article in Tables A1 and A2 (**1:** Grabski et al., 2012; **2:** Kiyuna et al., 2020; **3:** Kryshtopava et al., 2017; **5:** Parkinson et al., 2012; **6:** Peck et al., 2009). The last column reports the MNI coordinates for each region in each study. The coordinates of the regions classified as "Close to" in the web appendix are shown in italics. The third part of the table is identical to

the second but concerns the right side of the brain. Finally, the fourth part, which is also the last column, reports the average distance in millimetres between the left activation and the right activation. It is thus a measure of bilateralism. If the right/left correspondence was more than 10mm, the information was reported in different rows. The clusters and coordinates listed in Table A4 are represented in Figure A4 with several axial slices at different Z coordinates in MNI. The colors are assigned as follows: green = frontal lobe, red = temporal lobe, dark blue = parietal lobe, purple = insula, orange = putamen, light blue = thalamus and yellow = cerebellum.

Figures

Figure A1

Inclusion and exclusion criteria

INCLUSION

- Prospective study
- Group study
- Participants > 18 years
- Participants with no known vocal pathology
- Use of fMRI
- Sustained vowel phonation task as part of fMRI tasks

EXCLUSION

- No MNI/Talairach coordinates
- No separate results for groups/tasks

Figure A2

PRISMA flow diagram of study selection

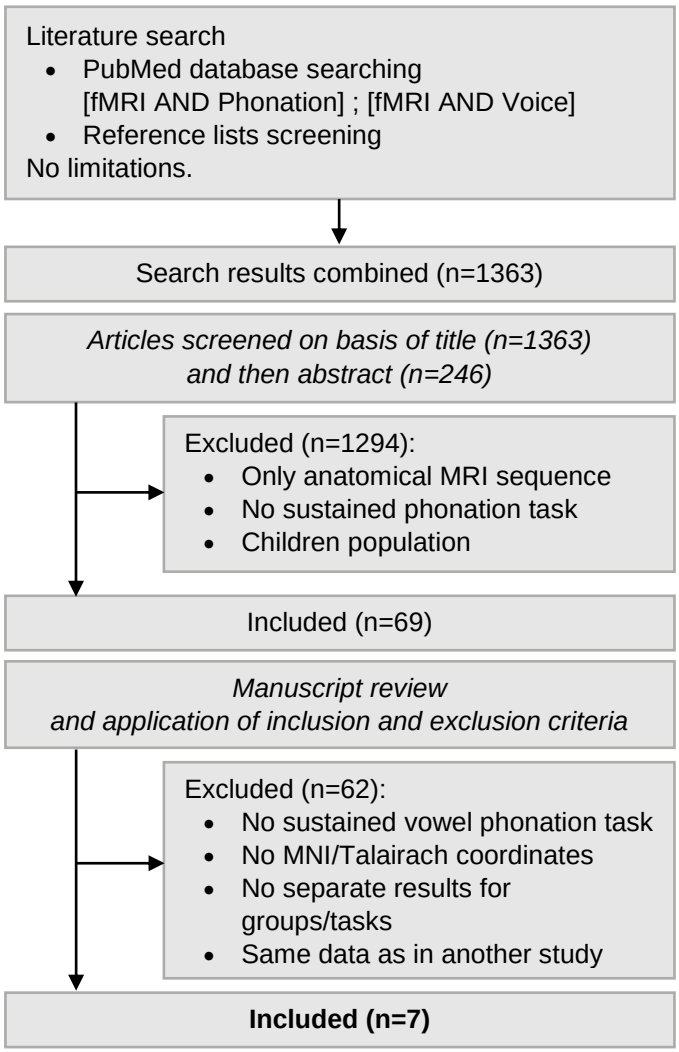


Figure A3 ***(in colors)***

Cluster revealed by the ALE meta-analysis

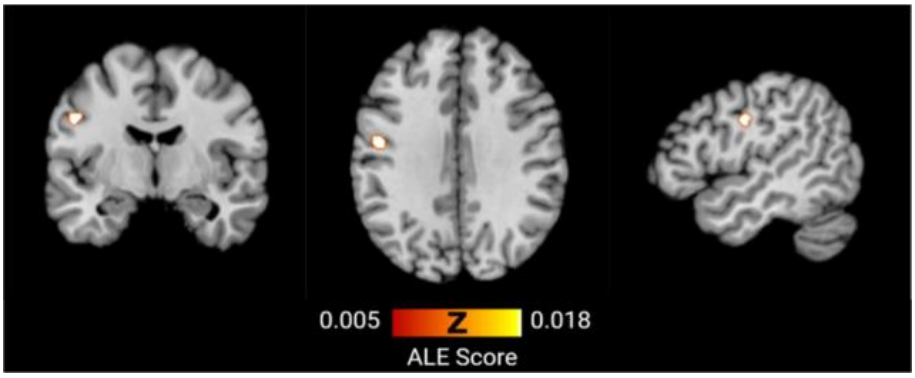
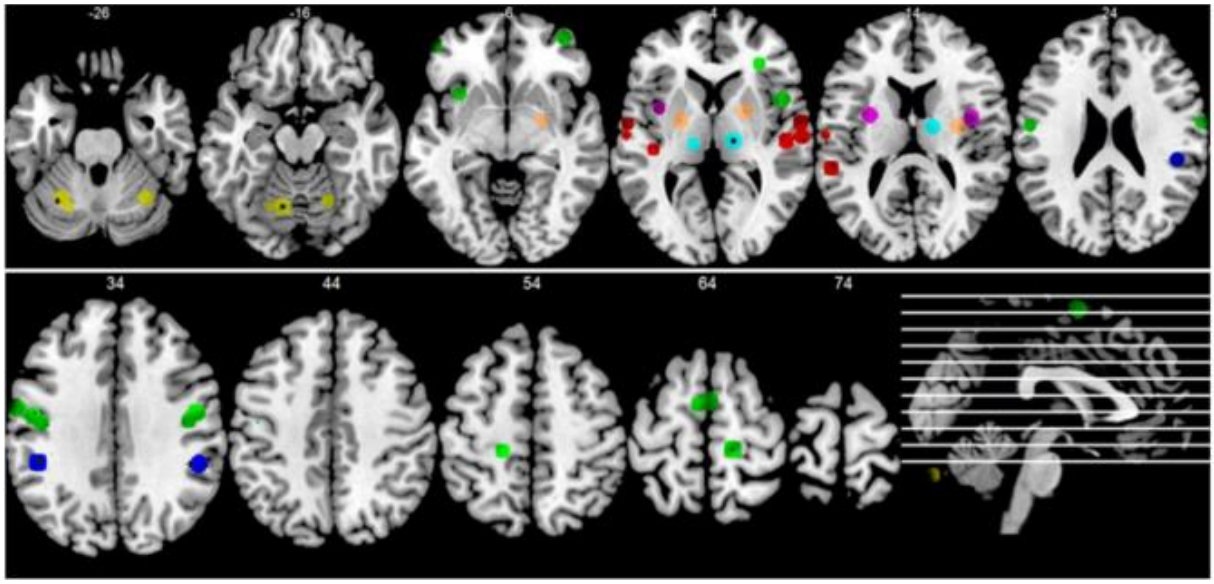


Figure A4 ***(in colors)***

Cluster and coordinate map



Note. The clusters and coordinates listed in Table A4 are represented on this brain map with several axial slices at different Z coordinates in MNI. The colors are specified in Table A4 and assigned as follows: green = frontal lobe, red = temporal lobe, dark blue = parietal lobe, purple = insula, orange = putamen, light blue = thalamus and yellow = cerebellum.

Vitae

Marie Dedry graduated in June 2017 with a Master's degree in psychology and educational sciences with a specialization in speech therapy. Currently, she is a doctoral student at the Université Catholique de Louvain (UCL), at the Psychological Sciences Research Institute (IPSY) and Institute of Neurosciences (IoNS) in Belgium, under the supervision of Professors Gauthier Desuter, Youri Maryn and Arnaud Szmalec. Her thesis includes research on different intervention and their respective impacts on the central and peripheral nervous systems, for early stage unilateral vocal fold paralysis. She also teaches at the School of Speech Therapy at UCL in Belgium.

Prof. Dr. Youri Maryn is clinical speech-language pathologist at European Institute for ORL-HNS (Department of Otorhinolaryngology and Head & Neck Surgery, GZA Sint-Augustinus, Belgium). He teaches on acoustic phonetics at Ghent University and on voice disorders at Ghent University College and Université Catholique de Louvain. He is post-doctoral researcher at University of Antwerp, serves as board member of the Flemish Association for Speech-Language Therapists, publishes on voice disorder management and acoustics, and he speaks at (inter)national voice meetings. His specific topics of interest are clinical voice assessment, voice disorder management, voice/speech acoustic and oral versus nasal speech production.

Arnaud Szmalec (PhD, 2005) is a professor in Psychology of Language at the Université catholique de Louvain and a visiting professor at Ghent University. As a cognitive (neuro-)scientist, his research interests include the cognitive underpinnings of (1) spoken and written language development, (2) language disorders and (3) bilingualism. He has published more than 60 scientific papers in his area of expertise and is a member of the National Committee for Psychological Sciences of the Royal Academy if Science, Letters and Fine Arts of Belgium.

Julie van Lith-Bijl, MD PhD, is the Director of Laryngology at the Voice and Swallowing Centre in Almere, the Netherlands, since 1998. She is also a general ENT specialist, working in a teaching hospital, with ENT specialization training. She has collaborated with the department of Laryngology in Amsterdam-UMC and Clinique Universitaires Saint-Luc, Brussels Belgium. She has a PhD (1998) in laryngeal nerve re-innervation involving the cat model. She is a member of the European Laryngological Society and is active in the international arena, lecturing on neurolaryngology.

Ir. Laurence Dricot finished her Ph.D. in neuroscience and thereafter she was hired by the UCL as expert in brain imaging. Dr. Dricot has a strong mathematical background through her studies in engineering, and she acquired a large expertise in various types of MRI data (brain morphometry, VLSM, diffusion imaging and fiber tracking, resting state and fMRI) and analysis (general linear approach, multivariate pattern analysis, independent component analysis, granger causality analysis and dynamic coupling modeling). This is witnessed by her publication record, which gives proof of her competence in a wide variety of MRI techniques.

Pr G. Desuter completed his Medical Degree and his Master in ENT- Head & Neck Surgery at the Louvain University, Belgium. He obtained a Master of Science degree in Health Care Management from the Harvard School of Public Health, Boston, USA, and a medical PhD degree from Leiden University, The Netherlands. He directs the Voice & Swallowing center of the St-Luke University hospital in Brussels, Belgium, and teaches, as professor of surgery and speech therapy at Louvain University. He is member of the board of the European Laryngological Society. He is author of numerous articles and books chapters on laryngology.