

Brain regions involved in motor control of speech

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1. Introduction

Human speech production requires a complex coordination of motor control for respiration, vocalization, and articulation. The neural mechanisms for speaking have been studied since the 17th century, yet many questions remain in determining the brain regions involved in speech production. In evidence of this, recent functional brain imaging studies examining normal subjects' articulation have resulted in inconsistent activation patterns.

The regions that are engaged in speech articulation spread over the cortical and subcortical areas. Within the cerebral cortex, the sensorimotor area is commonly observed to be active, while other areas often show disagreements. Broca's area has long been believed to be involved in speech articulation. Localized infarction within Broca's area, however, does not always cause classical Broca's aphasia [1], and some doubt has been posed with respect to the role of Broca's area in executing articulatory tasks without language processing. In fact, no activation was detected in this area in an experiment using positron emission tomography (PET) during articulation of a simple phrase [2] or during repetitions of heard words [3]. A lesion-based analysis by Dronkers [4] has shown that the left anterior insula is associated with the motor coordination of articulation. Wise *et al.* [3] measured brain activity while subjects repeated heard nouns, and showed activity of the left anterior insula. No activation of the insula during articulation was detected, however, during articulation in a PET study [2] or a functional magnetic resonance imaging (fMRI) study [5].

Other areas besides the cortex are also known to be involved in speech articulation. Clinical data of speech disorders in patients with cerebellar lesions or Parkinson's disease suggest that the cerebellum and the brain stem are engaged in the motor control of speech [6–8]. Ackermann *et al.* [9] showed activation of the right superior cerebellum during recitations of the names of the months by normal subjects. Wise *et al.* [3] also showed bilateral activation of the rostral paravermal cerebellum in repetitions of heard nouns. In producing syllables at a self-paced speaking rate, however, few significant responses of the cerebellum were detected [5]. There are not many studies regarding the activities of the brainstem and midbrain during speech. Wise *et al.* [3] reported activation of the dorsal brainstem during articulation. As far as we know, there have been no reports of the detection

of midbrain activation by PET or fMRI during speech.

As mentioned above, several studies have shown different activated regions especially in the subcortical areas during articulation. One of the reasons for this may be that some additional factors other than articulation were included in the tasks. The task design of the PET experiment in Murphy *et al.* [2] makes it possible to treat articulation independently from other tasks such as language processing, respiration, vocalization, etc. The measurement in their study, however, did not include the inferior cerebellum. In the present study, we conducted fMRI experiments to observe the overall brain activity during spontaneous speech production, while paying special attention to examine whether the insula and the cerebellum are involved in articulation. The experiment paradigm follows that of Murphy *et al.* [2] to separate the articulatory factor from those of vocalization, respiration, and hearing.

2. Experiment methods

Twenty-five healthy right-handed Japanese volunteers (18 men and 7 women, age range 25–56) participated in our fMRI experiments. Informed written consent for the study was obtained from all subjects in accordance with ATR Review Board Ethics Committee and ATR Review Board Safety Committee for Functional Resonance Imaging Research. None of them reported any history of neurological diseases or episodes.

The experiment was carried out using a 1.5 Tesla whole-body MRI scanner (Shimadzu-Marconi). Forty coronal slices (thickness = 4 mm with no gap) were acquired across the entire brain by means of a multislice echoplanar imaging sequence (TR = 5,000 ms, TE = 55 ms, FOV = 256 × 256 mm, matrix = 64 × 64). The coronal orientation was used to observe the cerebellum and brainstem without image distortion. Eighty-two image volumes were acquired in each session, and those included two dummy scans for the equilibration of T1 saturation effects. T2-weighted structural images were also obtained for anatomical reference.

Each subject underwent fMRI with their heads secured by pieces of foam rubber to minimize movement artifacts and with their eyes closed, while repeating Japanese phrases (meaning “Good morning, Good afternoon, Good evening”) under the following four conditions: A) normal speech (spoken aloud), B) mouthed speech (mouthing silently with normal breathing), C) unarticulated speech (voicing “ah...” without articulation), and D) internal speech (thought silently without any sound or movement). A block design (task and

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Table 1 Elements present in 4 speech-related conditions.

	(A) Normal	(B) Mouthed	(C) Unarticulated	(D) Internal
language	+	+	+	+
breath for speech	+		+	
vocalization	+		+	
hearing	+		+	
articulation	+	+		

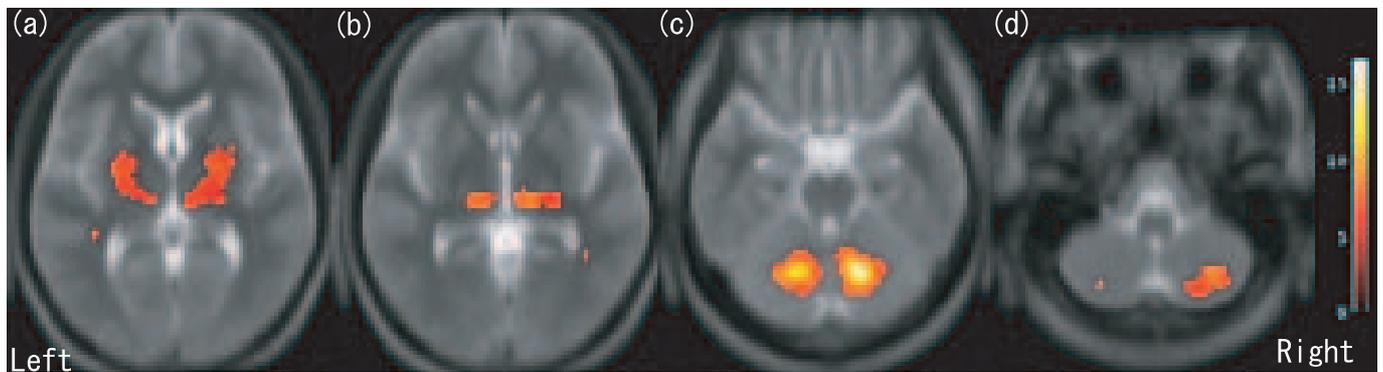


Fig. 1 Activation in the subtraction for articulation in (a) thalamus and putamen ($z = 4$), (b) midbrain ($z = -2$), (c) superior cerebellum (H VI, $z = -24$), and (d) inferior cerebellum (H VIII, $z = -54$).

rest conditions for 25 seconds each) was used in each session, and the subjects were informed of the alteration of two conditions by a sound via ear speakers. One of the problems in measurement of brain activity during speech using fMRI is the artifact in MR images that results from the subject's head movement during task performance. In order to reduce this head movement, each task was performed at a much slower speaking rate than normal (about 2 mora per s) and in a low voice. To familiarize the subjects with the speech conditions and to confirm the speech rate, the subjects practiced the four speech conditions before scanning.

In the four conditions described above, the task elements presented in each condition are shown in Table 1. The subtraction of C from A and the subtraction of D from B highlight the brain regions associated with articulation alone. The subtraction of B from A and the subtraction of D from C highlight the brain regions associated with speech breathing, vocalization, and hearing. This method for image contrast followed that of Murphy *et al.* [2]. In this letter we analyzed the subtractions of D from B and D from C.

The image processing and data analysis were performed with the SPM99 package (Wellcome Department of Cognitive Neurology, London, UK). The image volumes were realigned to the first volume, coregistered with the structural image, normalized spatially, and smoothed with an 8-mm FWHM Gaussian kernel. In the individual analysis, the subtractions B-D and C-D were assessed separately for each subject. The data was modeled using a box-car function convolved with a hemodynamic response function. High-pass filtering of the images was carried out to remove low-frequency artifacts corresponding to respiratory and cardiac effects. Low-pass filtering was also carried out to correct temporal autocorrelation in the fMRI data. In the group analysis (random effects

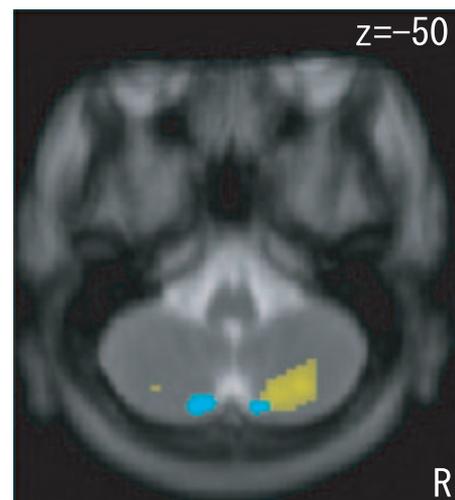


Fig. 2 Activation in the lower cerebellum in the subtraction for speech breathing and vocalization (blue) and for articulation (yellow) ($z = -50$).

between subjects), the contrast images for B-D and C-D made in the individual analysis were used as input for an SPM model employing a basic one-sample t-test. The statistical threshold was set at $p < 0.05$ (corrected for multiple comparisons). The anatomical reference of the cerebellum was based on the MRI atlas of the cerebellum by Schmahmann *et al.* [10].

3. Results

The subtraction for articulation, B-D, demonstrated bilateral activations in the sensorimotor cortex, thalamus,

putamen, midbrain, and the superior (H VI) and inferior (H VIIIA) regions of the cerebellum ($p < 0.05$, corrected, $T > 6.10$) (Fig. 1). Activations in the superior temporal gyrus ($x = -58$, $y = -36$, $z = 14$) and inferior parietal lobule ($x = -44$, $y = -46$, $z = 44$) were detected only in the left hemisphere.

Bilateral activations in the motor cortex ($x = 44$, $y = -10$, $z = 38$; $x = -58$, $y = 4$, $z = 38$) and in the inferior region of the cerebellum (H VIIB: $x = 12$, $y = -78$, $z = -50$; $x = -10$, $y = -76$, $z = -52$, H VIIIA: $x = 22$, $y = -68$, $z = -58$; $x = -22$, $y = -66$, $z = -60$) were detected in the subtraction for speech breathing, vocalization, and hearing, C-D ($p < 0.05$, corrected, $T > 6.08$). No activation was detected in the auditory cortex in this contrast. The inferior cerebellum was activated in the subtractions both for articulation (B-D) and for speech breathing, vocalization, and hearing (C-D), but the regions activated in the latter subtraction were more medial than in the former (Fig. 2).

In none of the subtractions was there activation in Broca's area, the supplementary motor area (SMA), or the insula.

4. Discussion

4.1. Speech breathing, vocalization, and hearing

In the subtraction for speech breathing, vocalization, and hearing, the bilateral motor cortex and the inferior cerebellum hemisphere were activated ($p < 0.05$, corrected, $T > 6.08$). No activation of the auditory cortex was observed, and this may be due to loud scan noise. Murphy *et al.* [2] reported that the motor cortex ($x = 54$, $y = -6$, $z = 36$), sensorimotor cortex (smc2: $x = 36$, $y = -18$, $z = 32$; $x = -38$, $y = -20$, $z = 32$), superior temporal gyrus, supplementary motor area, and thalamus were activated in the subtraction for speech breathing, vocalization, and hearing ($p < 0.001$, uncorrected). The motor cortex activated in the subtraction for speech breathing, vocalization, and hearing in the present study ($x = 42$, $y = -12$, $z = 36$) was near the smc2 ($x = 36$, $y = -18$, $z = 32$), which is the region that Murphy *et al.* [2] considered to be involved in speech breathing and vocalization. This region, however, was also activated in the subtraction for articulation in the present study. In the motor cortex, we could not separate the areas independently activated for articulation and for speech breathing and vocalization.

As for the inferior cerebellar hemisphere, the activated regions in the subtractions for speech breathing, vocalization, and hearing were more medial than those for articulation. These medial regions of the inferior cerebellar hemisphere (H VIIB, H VIIIA) are judged to be concerned with speech breathing and vocalization.

4.2. Articulation

In the contrast for articulation, the activated regions were the motor cortex, thalamus, putamen, midbrain, superior temporal gyrus, inferior parietal lobule, and the superior (H VI) and inferior (H VIIIA) regions of the cerebellum. The activated motor cortex associated with articulation in the present study includes sm1 ($x = 46$, $y = -16$, $z = 32$; $x = -42$, $y = -18$, $z = 32$) which Murphy *et al.* [2] associated with articulation. No activation of Broca's area was detected in the subtraction for articulation, and we infer that Broca's

area is not implicated in executing articulatory movements. Activation in the left superior temporal gyrus was detected only in the posterior part of the gyrus. Wise *et al.* [11] have reported that activation in this region responded to the motor act of speech, independent of the speaker's perception of his own utterances (they reanalyzed the data of Murphy *et al.* [2] using conjunction analysis). Our result confirms their statement that the region is involved in the motor control of speech.

Dronkers [4] has suggested that the left anterior insula is involved in articulatory planning. Wise *et al.* [3] showed activity of the anterior insula during articulation (repetitions of single nouns). However, the anterior insula was not activated in the present study. A possible reason for this may be that the speech task used in our experiment was well practiced and very easy to perform. The fact that the rate of articulation was slow to reduce head movement may also account for the discrepancy from the previous reports. The activation of the anterior insula has been detected during speech-related tasks, such as repetition of a heard single noun [3], and continuous overt recitation of the months of the year [12]. On the contrary, Riecker *et al.* [5] failed to show activation of the insula during repetitions of a monosyllable, a syllable sequence, and a lexical word. In the report of Riecker *et al.* [12], the insula was not activated during covert recitation, though the motor cortex and supplementary motor area were activated. These facts suggest that the anterior insula may be involved in rather complicated articulatory movement or in speech with auditory processing. Therefore, further studies are needed to determine whether the anterior insula governs the motor control of speech articulation. In the subtraction for articulation, activation was detected in the midbrain (proximate to the substantia nigra: $x = 14$, $y = -22$, $z = -4$; $x = -14$, $y = -22$, $z = -4$) as well as in the motor cortex and the basal ganglia. Based on the fact that there are projections from the substantia nigra to the putamen [13], this result suggests that the circuit of the primary motor cortex — putamen — substantia nigra is used for articulatory movement. The present study failed to detect activity of the pons or medulla, despite the common understanding that the hypoglossal, facial, and trigeminal motor nuclei in the pons should be activated during articulation. Many reasons can be given for this: hemodynamic characteristics in these regions may differ significantly from the cortical areas, or changes of signal intensity in these regions are assumed to be smaller than those in the cortex, and the sensitivity of the subtractive technique may be insufficient.

4.3. Activation of the cerebellum

Activation of the superior cerebellum (H VI) was observed in the subtraction for articulation but not for speech breathing and vocalization. This region is very similar to the activated region of the cerebellum associated with articulation in the result of Murphy *et al.* [2]. Grodd *et al.* [14] reported that activation in the superior cerebellum (H VI) was detected during a pursing gesture of the lips or a vertical movement of the tongue blade. This region was activated also in the subtraction for articulation in the present study, and the number of activated voxels was larger than that of Grodd *et al.* [14]. A similar region of the cerebellum was activated in

speech-related tasks [2,3,15]. Wildgruber *et al.* [15] showed that the region was activated only during the fast repetition (4 Hz and 5.5 Hz) of syllables. In the present study, activation in the superior cerebellum (H VI) was detected during slow articulation. These results show evidence that the superior cerebellum (H VI) is involved in the motor control of articulation regardless of speech rate.

In the present study, activation in the inferior cerebellum (H VIIIA) in the subtraction for articulation was larger in the right hemisphere than in the left. Previous studies [16–18] have proposed the possibility that the superior region of the right cerebellum is related to cognitive aspects of speech production. In our study, however, larger activation in the right cerebellum was observed only in the inferior region of the cerebellum, and was not detected in the condition of internal speech in which cognition is supposed to be a major factor. Thus, the activation of the inferior region of the right cerebellum seems to be related to the motor control of speech. Ackermann *et al.* [19] performed fMRI measurements during passive listening to click trains with various frequencies, and reported that a significant positive linear relationship between activation in the right inferior cerebellum (a similar region to that of the present study) and the frequency of the click stimuli. They suggested that the region performs the control of timing in verbal utterances. The larger activation in the right inferior cerebellum observed in the present study supports their suggestion.

5. Conclusion

We measured brain activity during speech production using fMRI on 25 Japanese subjects. The results showed that the motor cortex, putamen, thalamus, midbrain and cerebellum are involved in articulation. Involvement of the insula in executing articulation was not confirmed. The present study identified separated bilateral areas in the medial region of the inferior cerebellar hemisphere that are involved in articulation as well as in vocalization and breathing during speech.

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