

Research report

Phonemic manipulation in Japanese: an fMRI study

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Abstract

Phonological awareness is the ability to manipulate abstract phonological representations of language and is crucial to the process of learning to read. The neural substrates underlying this appear to be modality-independent at least in alphabetic languages. Japanese language has different orthographic “kana” system, in which each “kana” character strictly corresponds to a syllable. To investigate the neural substrates underlying phonological manipulation of the Japanese language, functional magnetic resonance imaging (fMRI) was used. Neuroimaging data were obtained from adult healthy volunteers during auditory and visual vowel exchange tasks, identical except for the modality of stimuli presentation: a voice and Japanese “kana” characters. Cerebellar vermis was activated by vowel exchange tasks of both modalities. The posterior parts of the superior temporal sulcus (STS) were active during the auditory tasks, suggesting that phonological representations of auditory stimuli are manipulated in this area. These findings are consistent with the previous studies with alphabetic languages. In contrast, the intraparietal sulci, which has been implicated for visuospatial tasks, was active during the visual tasks. This modality-dependent activation may indicate that the simple orthographic rule of the Japanese allows an alternate visual strategy to conduct the phonological awareness task, bypassing manipulation of phonological representation.

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1. Introduction

Reading ability is often a major part of the foundation of successful daily life functioning. A wide range of reading ability exists and, unfortunately, our present understanding of the process of learning to read does not allow the teaching of everyone to a high level of reading success or even to the maximum level possible for each person. An understanding of the brain areas involved in learning to read may aid in the development of teaching methods. Neurophysiology research has revealed that mature reading is performed by left-

hemisphere network of frontal, temporoparietal and occipitotemporal cortical regions. However, the neural substrates underlying reading acquisition are presently not well understood [53].

Developmental dyslexia is defined as a specific and significant impairment in reading ability that cannot be accounted for by any deficit in general intelligence or sensory acuity [58]. Identification of the specific neural deficits underlying dyslexia may increase understanding of the normal processes required for learning to read. In speech perception, the continuous sounds of speech must be encoded linguistic representations. It is holistic at first, and become increasingly segmental and more specific with age [22]. To learn grapheme–phoneme correspondence required for reading, spoken words must be segregated into discrete sub-lexical phonological representations (i.e., phonemes or syllables) [30,31] and map characters onto such

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phonological representations [44]. Phonological awareness is defined as the ability to manipulate, in an abstract form, the sound constituents of oral language [23]. Liberman [30] proposed that reading an alphabetic language requires phonological awareness. Dyslexic children exhibit deficits in various phonological awareness tasks that are used to assess reading skills, including phoneme segmentation, phoneme discrimination and rhyming judgment tasks [6,9,26,30,46,47,51,60].

There is much controversy, however, about the neurological and cognitive basis underlying the impaired phonological awareness in dyslexia [44,50]. The temporal processing theory argues that dyslexics have a subtle deficit in the perception of rapidly changing stimuli [23,42]. This deficit is thought to underlie the difficulty with auditory phonological awareness tasks, such as phoneme segmentation and phoneme discrimination tasks [6,9,30]. In contrast, the phonological theory argues that dyslexics have a specific impairment in representing and recalling speech sounds [44,45,49]. The impaired ability of dyslexics to perform phonological awareness tasks is evident not only in auditory tasks, but also in visual tasks, such as judging rhyming of nonwords or characters [42,46,47,51,60]. This suggests that the core deficit underlying impaired phonological awareness in dyslexia is the inability to manipulate phonological representations, either abstracted from auditory stimuli or recalled from visual stimuli.

Neuroimaging studies using auditory [7,11,62] or visual [42,43,46,47,51,60] phonological awareness tasks provide data consistent with the phonological theory. These studies have revealed that the left posterior temporal cortex, left inferior parietal cortex and inferior frontal cortex are involved in processing both auditory and visual phonological awareness tasks. Visually presented character strings are converted into phonological representations during either form of these tasks, and common neural substrates are therefore recruited for both modalities.

In Japanese populations, the prevalence of developmental dyslexia is much lower than in populations speaking alphabetic languages (Japanese 0.98% [33] to 1.7% [36] versus English 7.3% and Italian 3.6% [22,32]). Regarding the prevalence difference of dyslexia, Wydell and Butterworth [59] proposed an interesting explanation. They postulated that orthographies (print-to-sound translation) can be described in two dimension, transparency and granularity. They hypothesized that any orthography where the print-to-sound translation is one-to-one (transparent) will not produce a high incidence of phonological dyslexia. Furthermore, any orthography whose smallest orthographic unit representing sound is coarse (granular), again will not produce a high incidence of phonological dyslexia. They argued that transparent or granular systems do not require any complex mappings of sub-syllabic phonological component (phonemes) to the character level (graphemes). Failure to acquire these sub-syllabic skills is characteristic of developmental phonological dyslexia. Japanese populations use two differ-

ent types of writing systems: ideograms *kanji* and phonograms *kana* (*hiragana* and *katakana*). Kana system is transparent and kanji system is granular. And hence both transparency and granularity may explain the low prevalence of developmental dyslexia in Japanese [59]. *Hiragana* is the first writing system taught to Japanese children. A lower prevalence of developmental dyslexia in the Japanese population suggests that *kana* has some advantageous properties with respect to learning to read. First, the fundamental unit represented by a *kana* character is a mora, the unit of rhythm, which consists of a single consonant followed by a single vowel (C + V: open syllabic structure and hence we will use “syllable” through the text) [30]. Phonologically, identification of Japanese syllables is easier than of phonemes in alphabetic languages. A second advantage is that *kana* has a direct orthography–phonology correspondence, in which a single character corresponds to a single syllable [59]. For children learning to match phonological representations with their corresponding characters, a language with simple orthography–phonology correspondence is more consistent and thus, easier to learn [22]. These phonological and orthographical advantages of Japanese *kana* may aid in the process of constructing discrete phonological representations corresponding to *kana* characters.

The neural substrates underlying phonological awareness tasks in Japanese speakers is presently unknown and, to our knowledge, there are no previously reported studies examining this question. Because of the phonological and orthographical characteristics of the Japanese language, the neural substrates may be different from those underlying alphabetic languages. To investigate this, we employed functional magnetic resonance imaging (fMRI) to measure neural activity in Japanese participants during auditory and visual phonological tasks.

2. Materials and methods

2.1. Participants

Nineteen healthy volunteers (9 male and 10 female, mean age 23.3 ± 4.8 years) participated in this study. All participants were right handed according to Edinburgh's handedness inventory [40]. All of them were native Japanese speakers and had higher than college level education. There was no history of neurological or psychiatric illness or developmental disorders including reading disabilities. The protocol was approved by the ethical committee of the National Institute for Physiological Sciences, and all participants gave their written informed consent for the study.

2.2. Auditory tasks

To examine neural activity during phonemic manipulation of spoken words and nonwords presented as auditory

stimuli, we carried out fMRI scanning during an auditory vowel exchange task. Sixteen words and nonwords each consisting of three syllables were used as stimuli. For the task words, three-syllable words were selected from “the list of basic words for Japanese education” produced by the National Institute of Japanese Language [52]. The selected words were commonly used nouns that are most often written in *hiragana*. The task nonwords were produced from the selected task words by changing the vowel of the first syllable, thus maintaining the consonant and vowel structure of task words and nonwords except for the first vowel. This minimized any differences in difficulty of articulation of the task words and the task nonwords. All auditory stimuli consisted of a digitally recorded female voice (16 bit, 11.025 kHz sampling rate, using DigiOn Sound, DigiOn, Fukuoka, Japan). The maximum sound pressure (72 dB at the ear), frequency range and duration (mean 823 ± 39 ms) of each stimuli were adjusted using Goldwave (Newfoundland, Canada) and presented via earphones using Presentation software (Neurobehavioral Systems, CA, USA) on a microcomputer (Dimension 8200, Dell Computer, TX, USA). A digital pulse from the MRI scanner triggered the presentation of each stimulus. The participants were required to exchange the vowel of the second syllable to another vowel, “/e/”, without changing any consonants (Fig. 1), and to articulate the answer of each task. The responses were monitored through a non-magnetic condenser microphone and digitally recorded (10 kHz sampling rate) using Lab-View (National Instruments Japan, Tokyo, Japan). The participants were asked to fixate on a cross on the centre of a viewing screen throughout the session. The auditory vowel exchange session consisted of nine epochs, lasting 32 s each. Five epochs were for rest (R), two for nonwords (N) and two for words (W). The sequence of epochs in the

session was R-W-R-N-R-W-R-N-R. Eight words or nonwords were presented in each task epoch.

An auditory repetition task was performed as a control. The same set of task words or nonwords were presented in a different order, and the participants repeated them as they heard them without changing any syllables. All other aspects were identical to those of the auditory vowel exchange task.

2.3. Visual tasks

To examine neural activity during phonemic manipulation of written words and nonwords, we used the vowel exchange task using visual stimuli. Experimental settings were identical to those of the auditory vowel exchange tasks except for the mode of presentation. The task words and nonwords were presented as black characters against a white background at a visual angle of 18° (width) and 6° (height) projected using a LCD projector (DLA-M200L, Victor, Yokohama, Japan) onto a half-transparent viewing screen located behind the head coil viewed by the participants through a mirror. The visual stimuli were presented during the 2000-ms scanning interval.

A visual reading task was performed as a control. The same set of task words or nonwords were presented in a different order, and the participants read them aloud without changing any syllables. All other aspects were identical to those of the visual vowel exchange task.

Prior to the fMRI experiment, participants practiced each task with different sets of words and nonwords to ensure that they could make speech responses within the 2000 ms scanning interval without external cue for the response. During fMRI scanning, each participant performed four task sessions, one each of the auditory and visual vowel exchange tasks, and the auditory repetition and visual reading control tasks. Prior to each session, a specific instruction for read, repeat or vowel exchange was given by experimenter through headphones.

The same set of words and nonwords, with randomized order, were used throughout the experiment to minimize confounding factors by equalizing the perceptual input. The order of the tasks was counterbalanced between participants. After all fMRI sessions were completed, the participants were asked about their strategy for exchanging vowels during the experiment.

2.4. fMRI data acquisition

In each session, a time course series of 76 volumes was acquired using T2*-weighted, gradient echo, echo planar imaging sequences with a 3.0-T MR imager (Allegra, Siemens, Erlangen, Germany). Each volume consisted of 28 transaxial slices, with a thickness of 4 mm and a 1-mm gap between slices. These scans covered the entire cerebral and cerebellar cortex. Oblique scanning was used to exclude the eyeballs from the images. The time interval

Modality	Task words	Task (→“Response”)	
		Vowel Exchange	Repetition or Reading (control task)
Auditory	Words “Sa Ku Ra”	→“Sa Ke Ra”	→“Sa Ku Ra”
	Nonwords “Shi Ku Ra”	→“Shi Ke Ra”	→“Shi Ku Ra”
Visual	Words “さくら”*	→“Sa Ke Ra”	→“Sa Ku Ra”
	Nonwords “しくら”**	→“Shi Ke Ra”	→“Shi Ku Ra”

Fig. 1. Examples of task words and nonwords. The correct vowel exchange response for the word “Sa-Ku-Ra” (cherry blossom), for example, is “Sa-Ke-Ra” (nonword).

between two successive acquisitions of the same image was 4000 ms with a flip angle of 78° and 30-ms echo time. The clustered volume acquisition time was 2000 ms, leaving a 2000-ms silent period. The auditory stimuli were started 50 ms after the end of image acquisitions, and overt responses were completed within 2000 ms of the silent period. This design was intended to minimize the effect of scanning noise to the auditory stimuli and to minimize the motion artifact due to articulation related movement [20]. Due to the slow rise time constant of the regional blood flow to the neuronal activity (3–4 s) [2], this method can clearly detect activation even in the auditory cortex [14]. The field of view (FOV) was 192 mm and the in-plane matrix size was 64×64 pixels. For anatomical reference, T1-weighted fast spin echo images (TR=300 ms, TE=4.6 ms, FA= 90°) collected at the same positions as the echo planar images, and T1-weighted high-resolution 3D images covering the whole brain (TR=11.08 ms, TE=43 ms, FA= 6° , FOV=210 mm, matrix size= 256×256 mm) were obtained for each participant.

2.5. Data analysis

The data were analyzed using statistical parametric mapping (SPM99, Wellcome Department of Cognitive Neurology, London, UK) implemented in Matlab (Mathworks, Sherborn, MA, USA) [15–17]. The first 4 volumes of each fMRI session were discarded to allow for stabilization of the magnetization, and the remaining 72 volumes per session (a total of 288 volumes per participant) were used for analysis. Following realignment, all images were coregistered to the high-resolution, three-dimensional (3D), T1-weighted MRI, in reference to the anatomical MRI with T1-weighted fast spin echo images from locations identical to those of the fMRI images. The parameters for affine and nonlinear transformation into a template of T1-weighted images that was already fit to a standard stereotaxic space (MNI template) were estimated with the high-resolution, 3D, T1-weighted MR images by least square means. The parameters were applied to the coregistered fMRI data. The anatomically normalized fMRI data were filtered using a Gaussian kernel of 8 mm (full width at half maximum) in the x , y and z axes.

Statistical analysis was conducted at two levels. First, individual task-related activation was evaluated. Second, the summary data for each individual were analyzed using a random effect model [19] to make inferences at a population level.

2.5.1. Individual analysis

The signal intensity from images was proportionally scaled by setting the whole-brain mean value to 100 arbitrary units. The signal time course for each participant was modelled using a box-car function convolved with a hemodynamic response function, session effect and high-pass filtering (256 s). The explanatory variables were

centred to zero. To test hypotheses about regionally specific effects, the estimates for each model parameters were compared with the linear contrasts. For each task session, we compared the words and nonwords epochs separately with the rest epochs (comparisons 1–8, Table 1). To delineate neural substrates for vowel manipulation in the auditory modality, the activity during the auditory vowel exchange task was compared with that during the auditory repetition task. Similar comparisons were performed for the visual modality tasks. These comparisons were performed separately for words and nonwords (comparisons 9–12, Table 1). The set of voxel values resulting from each comparison yielded a statistical parametric map (SPM) of the t -statistic (SPM $\{t\}$). The threshold for SPM $\{t\}$ was set at $t > 3.61$ with degree of freedom (1,18) and $P < 0.05$ with a correction for multiple comparisons at the cluster level for the entire brain [18].

2.5.2. Group analysis with random effect model

The weighted sum of the parameter estimates in the individual analysis yielded “contrast” images, which were used for the group analysis [19]. Contrast images obtained via individual analysis represented the normalized task-related increase in the MR signal for each participant. For each comparison, one sample Student’s t -test was performed for each and every voxel within the brain to obtain population inferences. The resulting set of voxel values for each comparison yielded SPM $\{t\}$. The regions activated during each task were defined by the threshold for SPM $\{t\}$ set at $t > 3.61$ with degree of freedom (1,18) and $P < 0.05$ with a correction for multiple comparisons at the cluster level for the entire brain [18]. Acquired images for exchange tasks at this threshold were used for masking. To exclude any decreases in activity, the activated regions during the vowel exchange task compared with the auditory repetition task were searched in the regions, where were significantly activated regions during the auditory vowel exchange task (mask image) ($t > 3.61$ with degree of freedom (1,18) and corrected $p < 0.05$ at the cluster level). Masking was carried

Table 1
Comparisons for individual and group analysis

	Stimuli	Modality	Comparison	Mask
1	Nonwords	Auditory	Vowel exchange–rest	–
2	Nonwords	Auditory	Repetition–rest	–
3	Nonwords	Visual	Vowel exchange–rest	–
4	Nonwords	Visual	Reading–rest	–
5	Words	Auditory	Vowel exchange–rest	–
6	Words	Auditory	Repetition–rest	–
7	Words	Visual	Vowel exchange–rest	–
8	Words	Visual	Reading–rest	–
9	Nonwords	Auditory	Vowel exchange–repetition	+
10	Nonwords	Visual	Vowel exchange–reading	+
11	Words	Auditory	Vowel exchange–repetition	+
12	Words	Visual	Vowel exchange–reading	+

out in the same way for each comparison in the group analysis (Table 1).

3. Results

3.1. Task performance

The percent of correct responses for the auditory vowel exchange task ($93 \pm 8\%$ for nonwords and $97 \pm 5\%$ for words; mean \pm S.D.) was lower than those for the other tasks (repetition of nonwords $99 \pm 3\%$, repetition of words $100 \pm 0\%$, visual vowel exchange of nonwords $99 \pm 3\%$, visual vowel exchange of words $99 \pm 2\%$, reading of nonwords $100 \pm 0\%$ and reading of words $100 \pm 0\%$; Fig. 2). Differences in percentages of correct responses for the vowel exchange tasks compared with the control tasks in the same modalities were: auditory words, $-3 \pm 5\%$; auditory nonwords, $-5 \pm 8\%$; visual words, $-1 \pm 3\%$; and visual nonwords, $-1 \pm 2\%$. Two-way ANOVA showed that auditory versus visual stimuli presentation had a significant main effect on performance. The accuracy was lower for the auditory vowel exchange task compared with the visual task ($P < 0.05$). There was no significant main effect or interaction comparing word-to nonword-task performance ($P > 0.05$).

Fifteen of 19 participants answered the query regarding use of a strategy for the vowel exchange tasks. Twelve participants (80%) reported that they performed the vowel exchange tasks without a definable strategy. Two participants (13%) performed the task by utilizing Roman characters, in which a syllable is written with two characters (a vowel and a consonant). Another participant

utilized the rows of /e/ vowels in the Japanese syllabary table. No participant reported using different strategies for the auditory and visual tasks.

3.2. Movement effects of overt responses

All 19 participants could make overt response for both vowel exchange and control tasks within 2000 ms of the silent periods. The realign parameters that indicate the head motion during the scan were minimal (less than 0.8 mm for translation and 0.017 radian for rotation) and not task-epoch related. Hence, movement related artifact was successfully minimized.

3.3. Group analysis with random effect model

3.3.1. Task-related activity during nonword tasks

The areas of the brain exhibiting increased activity during all four nonword tasks were the preSMA (Brodmann area 6), bilateral precentral gyrus (Brodmann area 4 and 6) extending anteriorly to the middle frontal gyrus (Brodmann area 9), inferior frontal gyrus (Brodmann area 44, 45 and 47), anterior insula, bilateral thalamus, midbrain and cerebellum predominantly in the vermis (Fig. 3). During both auditory tasks, the bilateral primary and association auditory cortices (Brodmann area 41, 42, 21, 22) and left side of the intraparietal sulcus (IPS), including Brodmann area 40 and 7, were also active. During both visual tasks, the bilateral cuneus, lingual gyrus, fusiform gyrus (Brodmann area 17, 18, 19, 37), superior parietal lobule (LPs; Brodmann area 7) extending to the IPS, left middle occipital gyrus (Brodmann area 19), and posterior parts of the superior and middle temporal gyri, predominantly on the right, were also active.

The results of comparing activity during the vowel exchange tasks with that during the control tasks, which were derived from comparisons 9 and 10 in Table 1, are shown in Fig. 4 and Table 2. MR signal changes in five regions exhibiting increased activity were calculated for each participant using a spherical volume of interest (VOI) with a diameter of 12 mm (Fig. 4). VOIs were centred on the local maximum. Locations were (in Talairach's coordinates: x, y, z): right superior temporal sulcus (STS; 50, -38, 0), left STS (-46, -34, 0), right IPS (34, -56, 58), left IPS (-38, -54, 54) and cerebellar vermis (-2, -64, -34). The bilateral posterior parts of the STS, predominantly the left side, were significantly more active during the auditory vowel exchange task compared with repetition ($P < 0.001$, paired t -test). On the other hand, the bilateral IPS, extending into LPs (BA 7), were more active during the visual vowel exchange task compared with reading ($P < 0.001$, paired t -test). In the cerebellar vermis, the MR signal increased significantly more during both the auditory and visual vowel exchange tasks compared with the control tasks ($P < 0.001$, paired t -test).

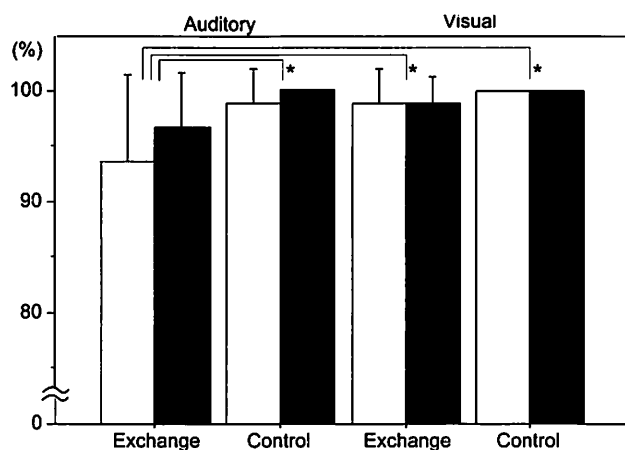


Fig. 2. The percentage of correct responses for each task. Data points represent the means \pm standard deviation (S.D.) from 19 subjects. The results of nonword and word conditions are represented by open and closed bars, respectively. The percentage of correct responses for the auditory vowel exchange task were lower than those for other tasks ($*P < 0.001$, two-way ANOVA).

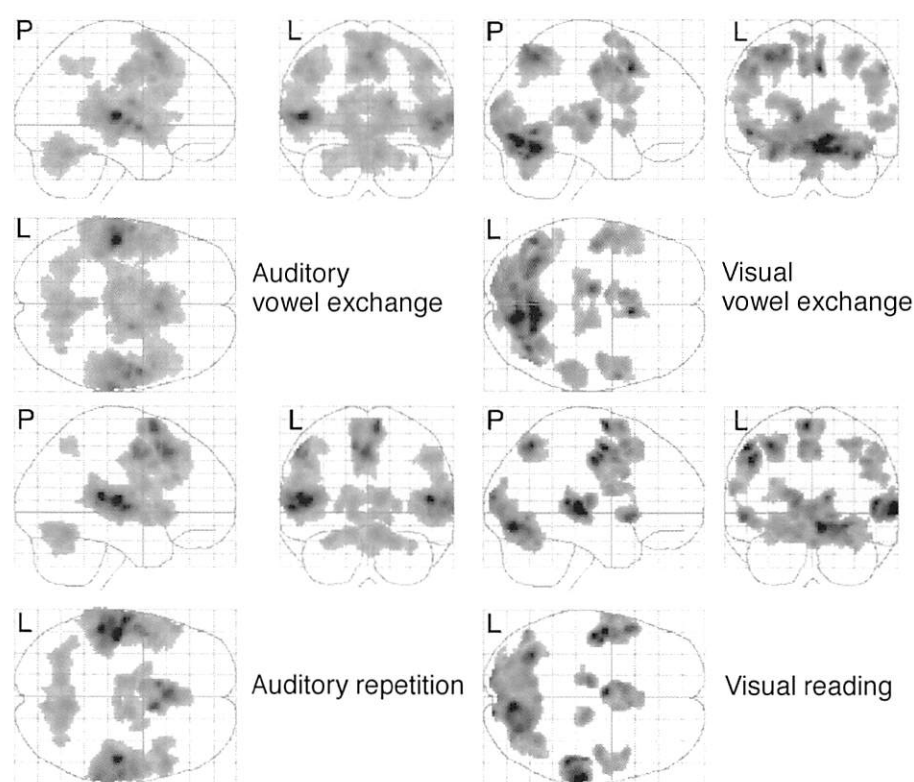


Fig. 3. Task-related activity during each nonword task (group analysis). The epochs of nonwords were compared with the rest epochs in the same sessions, and the more active areas are shown in standard anatomical space. Darker area represent higher activity. The threshold was set at $P < 0.05$ corrected for multiple comparisons at the cluster level. The 3D information was collapsed into 2D sagittal, coronal and transverse images. L, left; P, posterior.

3.3.2. Task-related activity during word tasks

Task-related activity increases during word tasks were smaller in degree but were similar in distribution to that observed during nonword tasks (Table 2).

4. Discussion

The results of the present study demonstrate that two different areas of the brain were active during phonological manipulation depending on the presentation mode of the stimuli: either auditory or visual. With auditory presentation, increased activity was observed in the bilateral posterior parts of the STS, predominantly the left side, while with visual presentation, increased activity was observed in the bilateral IPS, extending into LPs (BA 7). In addition, the cerebellar vermis was active during phonological manipulation with either auditory or visual stimuli presentation.

4.1. Task design

Phonological awareness tasks in alphabetic languages typically involve explicit judgments and/or manipulations of phonemes or other phonological components. The tasks require working memory and attention, but central to all these tasks is the manipulation of sub-lexical phonological representations [45]. The results of previous neuroimaging studies

suggest that similar neural substrates are involved in auditory and visual phonological awareness tasks, but prior to the present study, both auditory and visual tasks had not been directly examined within the same participants. Poldrack et al. [42] showed that the left inferior frontal region involved in visually presented rhyming judgment tasks is also active with rapidly changing auditory stimuli. Unfortunately, the auditory task used in their study (comprehension of compressed sentences) does not require the manipulation of sub-lexical phonological representations. To examine the neural substrates underlying the manipulation of phonological representations of auditory and visual stimuli, we used identical phonological manipulation tasks in both modalities.

Rhyming judgment tasks in the English language have been used as phonological awareness tasks in both auditory and visual modalities [6,30,42,46,47,60]. To create an equivalent task in Japanese, some consideration of Japanese orthography was required. Although phonemes are the phonological units corresponding to characters in the English language, characters do not consistently represent the same phoneme. To manipulate phonemes, visually presented character strings must be changed into the sequences of phonemic representations by phoneme-to-orthography correspondence rules, and these phonemic representations are treated in the same way as auditory stimuli. In Japanese *kana*, the phonological units corresponding to characters are syllables, and each character corresponds to only one syllable. Syllabic

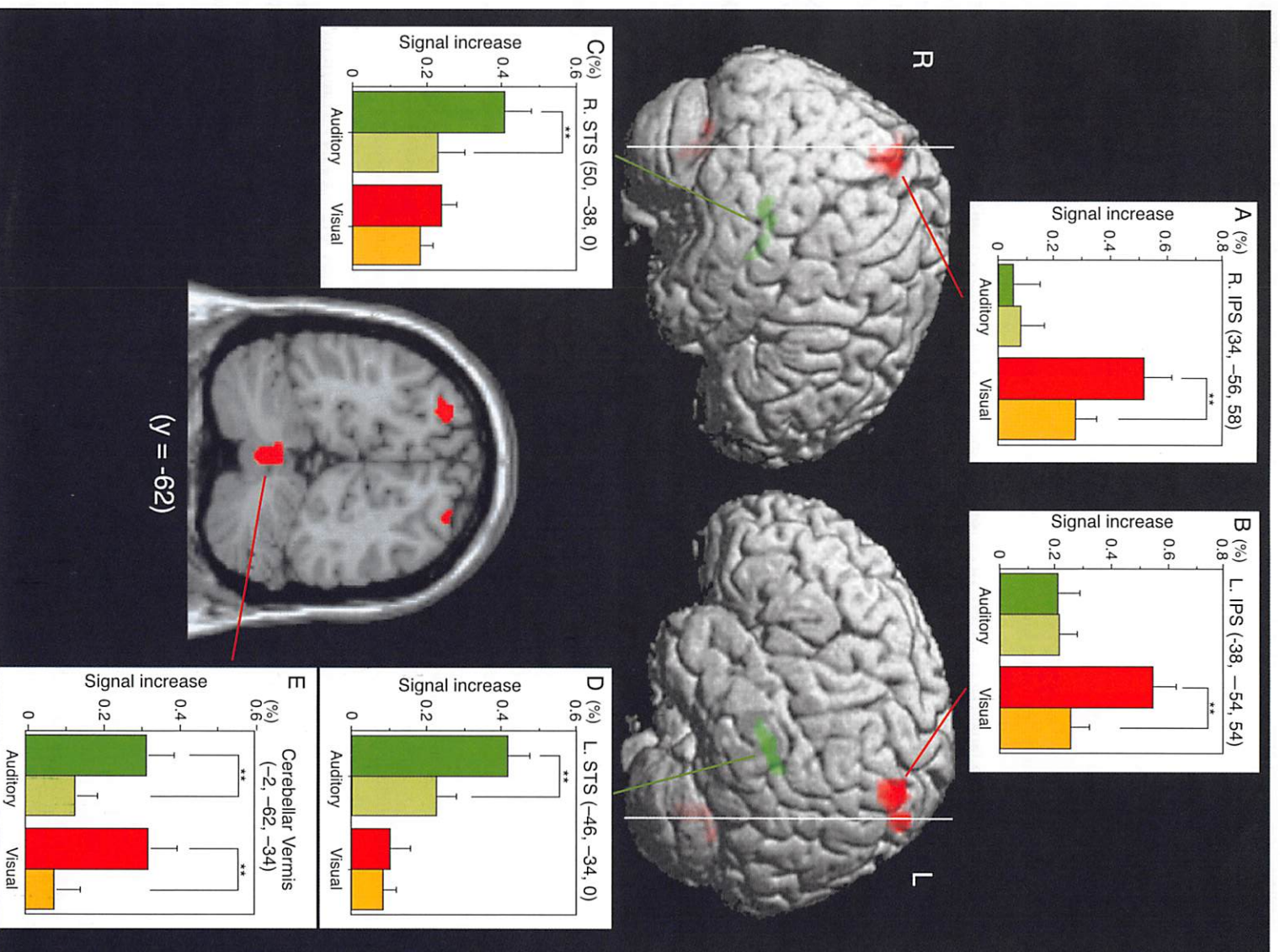


Fig. 4. Task-related activity in nonword tasks (group analysis). Areas exhibiting increased activity during the auditory vowel exchange task compared with the repetition task (green, bilateral posterior part of STS) and the visual vowel exchange task compared with the reading task (red, bilateral IPS and cerebellar vermis) are superimposed on canonical 3D images (upper) and a coronal section at Talairach's coordinate of $y = -62$ (lower middle). The threshold was set at $P < 0.05$ corrected for multiple comparisons at the cluster level. The bar graphs, A to E, showed task-related MR signal changes (%) during each nonword task in left IPS, right IPS, left STS, right STS and cerebellar vermis. Data points represent the means \pm SEM of 19 subjects. ** $P < 0.001$, paired t -test. L., left; R., right.

Table 2
Task-related activity revealed by vowel exchange task and control task comparisons

Comparison	Regions	Side	Nonwords			Cluster size	<i>t</i> -value	Words			Cluster size	<i>t</i> -value
			<i>x</i>	<i>y</i>	<i>z</i>			<i>x</i>	<i>y</i>	<i>z</i>		
Auditory	STS	L	–46	–34	0	122	7.35					
		R	50	–38	0	84	5.26					
Visual	LPs/IPS	L	–38	–54	54	233	5.32	–40	–52	52	78	5.01
		R	34	–56	58	117	4.91					
	Cerebellar vermis	–	2	–62	–34	144	5.19	–4	–76	–26	298	6.37

The local maxima with the threshold at $P < 0.05$ with a correction for multiple comparisons.

manipulation of auditory stimuli (syllable identification, syllable deletion and nonword reversal) have been used in phonological awareness tasks in Japanese [1,25,39]. Because of the strict character-to-syllable correspondence, however, syllabic manipulation of visual stimuli can be easily performed by character substitution, and thus cannot be treated as a phonological manipulation task. In the present study, we adapted identical vowel exchange tasks to both auditory and visual modalities. In vowel exchange tasks, participants must segment the target syllable into the elementary phonemes, i.e., consonant and vowel, and mentally manipulate those phonemes. Therefore, we assumed that the present vowel exchange task included the essential components of phonological awareness tasks in alphabetic languages.

4.2. Differences between word and nonword tasks

The results of the present study indicate that brain regions that were active were similar during both word and nonword tasks and that the signal increased more during phonemic manipulation in nonword tasks. This finding is consistent with previous studies [37,60]. It has been suggested that during phonemic manipulation tasks, nonwords are more directly decoded on a phoneme-by-phoneme basis during both reading and listening processes, and thus would be expected to be more demanding. Although the word processing presumably consists of the lexical (whole word) and sub-lexical (phoneme-by-phoneme) components, no specific activation for words is reported during phonological manipulation tasks without explicit semantic judgment. Mechelli et al. [34] suggested that word-specific effects could be differently expressed at the neural level, such as strength of functional connection or timing of activation, and that the imaging techniques currently available may not be sufficiently sensitive to detect them. Previously, nonwords have been used for phonological awareness tasks [11,37,42,43,46,47,60,62]. Therefore, further discussion will be mainly based on the result of nonword tasks.

4.3. Brain regions active during auditory and visual vowel exchange tasks

4.3.1. Modality independent activation

The cerebellar vermis was activated both auditory and visual vowel exchange tasks. The common activation of the

cerebellar vermis may be explained either by common mental process, i.e., phonological awareness or by non-specific demand of attention. Many previous studies reported cerebellar abnormalities in dyslexia, both in behavioral and cognitive impairments [38] as well as volume reduction [13]. However the contribution of the cerebellar vermis to the phonological awareness task is not clear. The double-deficit hypothesis [57] proposes that deficits in phonological awareness and impaired rapid automatized naming (RAN), which is derived from cerebellar deficits, are separable sources of reading dysfunction. On the other hand, Nicolson et al. [38] suggested that cerebellar deficit reduced the quality of articulatory representation, which in turn lead to impaired phonological awareness. The cerebellar activation of the present study suggests that cerebellar vermis may contribute to the phonological manipulation task.

The cerebellum, including vermis, was the part of neural substrates for sustained attention (vigilance) [29]. Therefore, another possible explanation for present cerebellar activation is the greater demand for sustained attention during vowel exchange task conditions than during the control conditions.

4.3.2. Modality dependent activation

Previous neuroimaging studies using phonological awareness tasks with stimuli presented in both auditory [7,11,62] and visual modalities [42,43,46,47,51,60] have reported activity in the superior posterior temporal cortex, left inferior parietal cortex and Broca's area essentially the same location irrespective of the presentation modality (visual or auditory). On the other hand, present study with Japanese phonemic awareness tasks showed the modality dependency: the STS with auditory presentation, and the IPS with visual presentation. The previous studies involved alphabetic language-speaking participants and tasks in alphabetic languages. In contrast, the present study involved Japanese-speaking participants and tasks in Japanese. Although the utilized tasks are not identical, the modality-dependent activation patterns of phonological awareness tasks in the present study may be due to the characteristics of Japanese language, which allows different strategies between modalities.

The results of the interview after experiments could not reveal the task-specific strategy, because most of the participants were not aware of their strategy for conducting either

the auditory or visual vowel exchange tasks. However, the results of task performance may imply the difference of such unconscious task strategies. The visual vowel exchange task was performed more accurately than the auditory vowel exchange task. Any differences in task difficulty related to perceptual processes were controlled for by comparing with a control task in each modality. In the auditory phonemic awareness task, auditory input is processed without orthographic conversion. In the visual task, visual input is presumably converted to the auditory information. And hence higher accuracy in visual task in the present study may reflect availability of the additional information for performing the task.

The posterior part of the STS was more active during the auditory vowel exchange task compared with the control repetition task. Many neuroimaging studies have reported increased activity in the middle to posterior part of the STS, predominantly on the left side, during speech and human voice perception [3–5,21,56]. The posterior part of the left STS is active both during listening to speech and mentally recalling words [56]. Wise et al. [56] postulated that the left posterior STS is the region in which the temporally ordered sequence of sounds that comprise a heard or recalled word are transiently represented. The activation in the posterior STS in the present study, located in between them, may thus suggest its contribution to the manipulation of phonemic representations abstracted from auditory stimuli.

A recent functional imaging study revealed that the left posterior temporal cortex was consistently activated in children through adulthood during implicit reading task, and that its activity was correlated with children's phonological skills [53]. This suggests that the posterior temporal cortex, probably including the STS, may be engaged in the reading acquisition, at least in alphabetic languages.

During the visual vowel exchange task, there was increased activity in the bilateral IPS extending to the LPs. This region is the part of the dorsal visuospatial stream, which projects from the occipital cortex to the parietal region [8,35,54]. Functional neuroimaging studies have revealed that the posterior parietal cortex, especially around the IPS, is involved in a variety of visuospatial tasks [10]. The posterior parietal region is also involved in mentally performed verbal tasks [46,51,60]. The regions involved in spatial and verbal mental operation, however, appear to be different [24,48]. Hanakawa et al. [24] used fMRI to study neural activity during three types of mental-operation tasks, numerical (serial mental addition), verbal (sequential advance of the days of the week), and spatial (mentally moving within a 2D grid). The spatial mental-operation task primarily involves the bilateral LPs (Brodmann area 7) and the numerical and verbal mental-operation tasks involve the left side of Brodmann area 40 and 7, including the IPS. In the present study, activity in the bilateral IPS extending to the LPs increased specifically during the verbal vowel exchange task. This is more similar to the activity observed in the Hanakawa's study during spatial mental operation

than verbal mental operation tasks. Hence, we speculate that a similar visuospatial mental operation may be utilized for the visual vowel exchange task.

One participant specifically identified using the Japanese syllabary table in the vowel exchange tasks. It may be that other participants also used the same strategy for these tasks even if they were not aware of, at least as possibility. This speculation is coming from the fact that most Japanese learn *kana* according to this table, in which *kana* characters are systematically placed in a table of 5 vowels and 10 consonants (5 by 10 matrix; Fig. 5). Japanese *kana* has a strict systematic vowel and consonant combination structure, allowing simple tabulation. The Japanese syllabary table may be utilized as a location map of phonemes. This raises the possibility that the visuospatial stream was involved in the manipulation of Japanese phonemes when the task presented as *kana* characters, which do not represent phonemes per se. This visuospatial strategy may be utilized specifically in visually presented tasks, because, in auditory tasks, acoustic information of task sounds implies phonemic cues.

In the present study, the inferior frontal and parietal regions were active during all four tasks, and this activity was greater during the vowel exchange tasks although it did not reach the statistical threshold. The superior posterior temporal cortex, the left inferior parietal cortex and/or Broca's area are frequently involved in performing alphabetic phonological awareness tasks in alphabetic languages such as English [7,11,42,43,46,51,60,62]. It has been postulated that the posterior superior temporal lobe constitutes the primary substrate for constructing sound-based (phonological) representation and that the inferior frontal cortical fields are involved in coding speech in an articulatory context (articulatory representation) that is not necessarily for overt speech only [61,62]. Hickok and Poeppel [27] hypothesized that the inferior parietal lobe contains an important interface system mediating between phonological and articulatory representations of speech. Such a network might be established in development as part of the process of learning to articulate speech where the young child must compare the sound of words uttered by others with those

consonants									
w	r	y	m	h	n	t	s	k	
わ	ら	や	ま	は	な	た	さ	か	あ
wa	ra	ya	ma	ha	na	ta	sa	ka	a
	り		み	ひ	に	ち	し	き	い
	ri		mi	hi	ni	chi	shi	ki	i
	る	ゆ	む	ふ	ぬ	つ	ず	く	う
	ru	yu	mu	fu	nu	tsu	su	ku	u
	れ		め	へ	ね	て	せ	け	え
	re		me	he	ne	te	se	ke	e
ん	ろ	よ	も	ほ	の	と	そ	こ	お
n	ro	yo	mo	ho	no	to	so	ko	o

Fig. 5. The Japanese syllabary table for *hiragana*.

that he or she produces as a mechanism for tuning articulatory processes to the target language [12,55]. Attention to phonemic segments would seem to be critical in this developmental process, and perhaps this auditory-motor interface network remains available to the adult and is useful in the performance of sub-lexical speech tasks [27]. For detailed analysis of the phonological components, alphabetic readers may compare the phonological representations with their articulation. The ability to perform phonological awareness tasks is thought to ‘spurt’ with acquisition of literacy [22,25]. This is because the feedback provided by grapheme information helps to represent the segmental information of spoken words, especially for languages with simple orthography–phonology correspondence, such as German [22]. Because each *kana* character strictly corresponds to a syllable, learning *kana* characters may help with representation of syllables without referring to their articulations. Therefore, after *kana* characters are mastered, identifying or recalling phonological representations of *kana* may not require reference to articulations.

In the present study, auditory and visual phonological manipulation tasks using the Japanese language resulted in increased activity in brain regions different from those previously shown to be involved in articulatory representation. At the syllabic level, *kana* characters help in constructing and manipulating syllabic representations. At the phonemic level, which is not represented in characters, the position in the Japanese syllabary table may provide cues for phonemes. Therefore, the contribution of phonological representation in phoneme manipulation for the Japanese language may be less than for alphabetic languages, especially for tasks with visually presented *kana*.

4.4. Implication for dyslexia in the Japanese population

Previous studies suggest that dyslexics who read different languages have a common deficit in phonological awareness, which may be due to a universal basis in the brain [41]. Although impairment of phonological representation may be the same in Japanese dyslexics, their impairment may be easily compensated at the level of character-to-syllable mapping because of the simplicity of the Japanese syllabic structure. This raises the possibility that at the first stages of reading acquisition, especially for children with the inability to manipulate phonological representations, utilizing a table or visual strategy may help in understanding the phonological structure of the spoken language. Indeed, there is a case report supporting this idea. Kaneko and colleague [28] reported a Japanese dyslexic child whose response time for reading a character was dependent on its distance from the origin of the table (/a/). One interpretation of this finding is that this child used the table to search for the target character, and thus the reaction time reflected the distance within the matrix of the table. In addition, a tool similar to the Japanese syllabary table has been used to teach dyslexic children in alphabetic languages [31,32]. To

teach alphabetic orthography, the teachers place basic vowels in vertical columns in a table and systematically add preceding and following consonants to the vowels. Utilizing a table such as this may help dyslexic children understand the phonological structure of spoken language and how characters correspond to sounds.

In conclusion, the results of the present study demonstrate that different areas of the brain are active during phonological awareness tasks in Japanese *kana* compared with previously identified areas involved in similar tasks in alphabetic languages. Furthermore, the active areas depended on the sensory modality of stimuli presentation: auditory or visual. This modality-dependent activation may indicate that the simple orthographic rule of the Japanese allows an alternate visual strategy to conduct the phonological awareness task, bypassing manipulation of phonological representation.

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