CORTICAL REORGANIZATION ASSOCIATED WITH THE ACQUISITION OF MANDARIN TONES BY AMERICAN LEARNERS: AN FMRI STUDY

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ABSTRACT

This study employed functional magnetic resonance imaging (fMRI) to investigate cortical effects of learning Mandarin tones by native speakers of American English. Six American learners were scanned while listening to Mandarin tones. The learners then participated in a two-week Mandarin tone training program, after which they were scanned again. Regions of brain activation in the perception of tones before and after training were compared. Results showed significant cortical change in activation areas in the temporal-lobe language-sensitive regions (Wernicke’s area), and in the frontal-lobe language-sensitive regions (Broca’s area) in the left hemisphere, as well as the homologous areas in the right hemisphere. These results are discussed in terms of changing cortical representations in language learning.

1. INTRODUCTION

Research in language acquisition has traditionally been dominated by the Critical Period Hypothesis (CPH), stating that cerebral lateralization occurs after puberty, accompanied by a loss of neurological plasticity of the brain, resulting in a reduction in language learning ability [1]. However, recent research indicates that cortical representations are continuously shaped by experience [2]. This study employed functional magnetic resonance imaging (fMRI) to investigate cortical effects of learning Mandarin tone contrasts by adult native speakers of American English.

Mandarin has four lexical tones, differing primarily in terms of fundamental frequency (F0). Research has generally found that lexical tone is predominantly lateralized in the left hemisphere [3, 4], while other pitch-related discrimination abilities are predominantly lateralized in the right hemisphere [5]. Some interesting questions then arise as to what the hemispheric activation pattern is for adult learners of a tone language (e.g., American learners of Mandarin), and whether and how the pattern is changed in the process of learning. Behavioral studies on American learners of Mandarin have shown that learners’ tone identification can be significantly improved after short perceptual training [6]. This procedure provides an ideal situation for studying the cortical representations in the process of learning.

2. METHOD

Participants. Six native speakers of American English (4 females, 2 males) without speech and hearing impairments participated in the study. They were all students at Columbia University who had taken Mandarin Chinese courses for one semester, and they had no experience with a tone language prior to learning Mandarin. All participants are right-handed, as assessed by the Edinburgh handedness inventory. All were paid for their participation.

Stimuli. Two hundred and twenty different real monosyllabic Mandarin words were selected: 40 (10 per tone) were used in the pre/post-test, and 180 (45 per tone) were used in training. Audio recordings were made of five (1 for pre/post-test, and 4 for training) native speakers of Mandarin producing each word in isolation.

Imaging. A 1.5-tesla General Electric magnetic resonance scanner was used to obtain T2*-weighted images with a gradient echo pulse sequence which was sensitive to magnetic resonance signal changes induced by alteration in the proportion of deoxyhaemoglobin in the local vasculature accompanying neuronal activation [7]. The in-plane resolution was 1.5 mm by 1.5 mm, and slide thickness was 4.5 mm. Twenty-one contiguous axial slices of brain, which covered the entire cortex for a subject, were obtained. Thirty-six images were taken for each run, out of which 30 were included: a baseline (resting) period of 10 images (40 sec), a stimulation period of 10 images (40 sec), and a baseline (recovery) period of 10 images (40 sec).

Procedure. The study had three stages: pretest scanning, training, and post-test scanning. In the pretest, subjects were individually scanned in three pairs of identical runs. The first two runs were to identify subjects’ brain activation for motion and vision, during which subjects were asked to tap their right-hand fingers while seeing a flashing checkerboard, which was back projected onto a screen located at the foot of the scanner.
Subjects viewed the checkerboard through a slanted mirror incorporated into the head coil and located above their head. The next two runs were to determine subjects’ brain activation during general auditory processing, during which subjects were presented with pure tone sweeps through headphones which were designed to reduce background scanner noise. The last two runs were the Mandarin tone identification runs. Twenty Mandarin words (each with one of the four tones) were presented in each run, with an inter-stimulus-interval of two seconds. Subjects were asked to identify which tone s/he heard (through the headphones) after each stimulus, by pointing to the corresponding tone mark located on the screen. Subjects indicated their responses with a laser pointer, tied to their right hand. An experimenter was standing at the side of the scanner to take down subjects’ responses.

After the pretest scanning, the subjects participated in a two-week Mandarin tone training program, consisting of eight sessions of 40 minutes each, during which they were trained auditorily with the stimuli produced by native speakers of Mandarin (for details of the training procedure, see [6]).

When training was completed, the subjects received the post-test scanning, which was identical to the pretest scanning.

Analysis. All brain images were computationally aligned to allow direct comparisons between pre- and post-test scanning for individual subjects, and a two-dimensional gaussian filter was applied. Activation of each voxel in the image was determined by a multistage statistical analysis of the differences in intensity between stimulation and both baseline periods and required statistically significant signal changes on two identical runs. Two stages of analysis were taken for each subject to determine cortical change between pre- and post-test tone identification: 1) in order to eliminate the irrelevant visual, motor, and auditory information in the two tone identification runs, a “logical exclusion” strategy was employed to “subtract” activation in the “finger-tapping and checkerboard” and “tone sweep” runs from the “tone identification” runs, leaving only the activation unique to Mandarin tone identification. This was done for both pre- and post-test scanning; and 2) the same strategy was applied to subtract activation unique to pretest tone identification from that unique to post-test tone identification, leaving only the activation in tone identification after training. For each active cluster for each image, anatomical labels, Brodmann’s Areas, and atlas sectors were assigned based on judgments of brain and atlas correspondence [8]. Post-training brain regions that were consistently activated (conserved areas) across all subjects were then determined.

Native speaker reference. To serve as a reference, tone identification data were also acquired from one right-handed female native speaker of Mandarin Chinese (YW), using the same stimuli and procedure as the pretest scanning for the American learners.

3. RESULTS

The behavioral and the imaging data indicate evidence of cortical change due to behavioral training. As is presented in Table 1, the behavioral data show that learners’ Mandarin tone identification consistently improved after training; the one exception being subject MR, who reached ceiling performance in the pretest.

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Pretest</th>
<th>Post-test</th>
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<tr>
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Table 1: Percent correct identification of the Mandarin tones before and after training by the American learners.

Figure 1 illustrates a representative image (slice 7, horizontal sector +8mm, Talairach and Tournoux) for the native Mandarin speaker. Significantly activated voxels (p<.01) are colored yellow. The right side of the brain (indicated as R) is shown on the left side of the images according to radiological convention. For the native Mandarin speaker, activity is found in the superior temporal gyrus (Brodmann’s area 22) in the left hemisphere, corresponding to the language-sensitive region Wernicke’s area.

Figure 2 illustrates a representative image (slice 7, horizontal sector +8mm) for the American learners (subject RO, female), showing the activation in response to Mandarin tone identification in the pretest (2a), post-test (2b), and subtraction activation unique to post-test identification (post-test activation minus pretest activation) (2c). For the pretest (Figure 2a), distinct areas of activation are observed in the left hemisphere in the inferior frontal gyrus (Brodmann’s area 45), corresponding to the language-sensitive region Broca’s area; the superior temporal gyrus (Brodmann’s areas 22, 42), corresponding to Wernicke’s area. Significant activation is also found in the right hemisphere in the superior temporal gyrus (Brodmann’s area 22). For the post-test (Figure 2b), activation foci are found in the inferior frontal gyrus (Brodmann’s areas 44, 45) in the left hemisphere, the superior temporal gyrus (Brodmann’s areas 22, 42) in the left hemisphere, and the homologous areas in the right hemisphere. Excluding the activated areas that are common for both the pre- and the post-test, Figure 2c shows the activation foci unique to the post-test, in the inferior frontal gyrus and the superior temporal gyrus (Brodmann’s areas 44, 45, 22, 42) in the left hemisphere.
hemisphere; Brodmann’s areas 44, 45, 22 in the right hemisphere). Together, Figure 2 reveals that additional language-sensitive areas in both hemispheres are activated in tone identification after training. In the pretest, no activation is observed in the right hemisphere for the language-sensitive region equivalent to Broca’s area, a pattern that is different from the post-test.

**Figure 1:** A representative axial slice (slice 7) from a native Mandarin speaker (YW), showing activation in response to Mandarin tone identification. Voxels that pass the multistage statistical criteria at p<.01 are yellow. WA: Wernicke’s area. R indicates the right side of the brain.

**Figure 2:** A representative axial slice (slice 7) from Subject RO, showing brain activation in response to Mandarin tone identification in the pretest (a), post-test (b), and activation unique to the post-test (c). Broca’s area (BA) and Wernicke’s area (WA), and the equivalent areas in the right hemisphere are labeled.

An analysis of the other five subjects reveals similar patterns to those for RO shown above, although individual differences do exist. Table 2 shows the individual patterns across subjects for the language-sensitive regions that are active in Mandarin tone identification in the post-test but not in the pretest, and the conserved active regions. It reveals that, across subjects, additional language-sensitive areas in both hemispheres are activated after tone training.

<table>
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<tr>
<th></th>
<th>RO</th>
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**Table 2** Anatomical and Brodmann’s areas per Subject and Hemisphere, and the conserved Brodmann’s Areas across subjects that are activated in Mandarin tone identification after training. LH: left hemisphere; RH: right hemisphere; GFi: inferior frontal gyrus; GTs: superior temporal gyrus; Con: conserved Brodmann’s Areas.

### 4. DISCUSSION

Several general observations can be made based on the above results. First, for the American learners, bilateral activation was generally observed for both pre- and post-training images, whereas for the native Mandarin speaker, significant activation was found only in the language-specific region, Wernicke’s area. Although the native speaker data are based on one subject only, these results are consistent with previous findings in behavioral studies that lexical tones are predominantly
lateralized in the left hemisphere by native speakers, whereas they are bilaterally lateralized by non-native speakers [3, 4]. It is possible that, when processing Mandarin tones, these American learners were influenced by the functional use of pitch in their native language, which is generally a right-hemisphere property. It is also possible that more brain regions are needed to handle new linguistic contrasts that are different from the native language. This is also shown by the difference between the pre- and post-training images, one of the primary observations in this study. That is, additional areas are activated after training, especially in the right hemisphere in the region equivalent to Broca’s area (cf. Figure 2, Table 2). These cortical changes provide some evidence of neural plasticity in the process of language learning in adult learners, as is also evidenced by clinical studies [9], showing the right hemisphere can take over language acquisition functions when the left hemisphere is surgically removed. Thus, it seems that the adult human brain still has great capacity to change - new brain regions can be recruited in language learning. Another important observation is the activation in Broca’s area and that of its right-hemisphere equivalent after training. It is interesting to note that for the language perception task in this study, the most noticeable change occurred in Broca’s area and its equivalent, rather than in Wernicke’s area. Other studies have also reported that for late language learners, native and second languages are spatially separated within Broca’s area rather than Wernicke’s area [10]. It might be that Broca’s area is a critical area for language learning.

5. CONCLUSION

The preliminary results discussed above reveal significant cortical change in the identification of Mandarin tones due to perceptual training. More detailed analyses in terms of the amount and location of the activated voxels in the pre- and post-test images are underway to quantitatively determine the magnitude and nature of cortical reorganization in the process of learning Mandarin tones.

6. REFERENCES


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