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Cortical Activation of Level-to-Contour Tone Changes in Different Vowel Duration Indexed by Mismatch Negativity

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Abstract: Mismatch Negativity (MMN) generally increased as a function of the degree of discrepancy from the standard-stimulus duration. The MMN generator is indeed sensitive to even very small amounts of stimulus energy. The main objective of this study was to investigate the cortical activation of level-to-contour tone changes in different vowel duration indexed by mismatch negativity. Twenty-two healthy right-handed adults participated in this study. It was found that the long-to-short vowel duration changes with level-to-falling/rising and falling/rising-to-level tone changes perception elicited MMN between 196-220 msec with reference to the standard-stimulus Event-related Potentials (ERPs). The long-to-short vowel duration and level-to-falling/rising tone changes elicited a strong MMN bilaterally for both native and nonnative speakers of Thai, unlike short-to-long vowel duration and falling/rising-to-level tone changes. Source localization analyses performed using Low Resolution Electromagnetic Tomography (LORETA) demonstrated that sources were obtained in the Middle Temporal Gyrus (MTG) of the left hemisphere and in the Superior Temporal Gyrus (STG) of the right hemisphere for both subject groups.

Key words: Event-related potential, Mismatch negativity, sound, tone, vowel

INTRODUCTION

In earlier studies (Gandour, 1998; Gandour *et al*., 2000; Hsieh *et al*., 2001), Chinese and English listeners did not show the same Left-hemisphere (LH) lateralization as Thai listeners when making perceptual judgments of Thai tones. In addition, Chinese and English listeners were asked to make perceptual judgments of Chinese tones, consonants and vowels. Chinese listeners showed Left-hemisphere lateralization for both suprasegmental and segmental phonological units (Hsieh *et al*., 2001). These earlier studies suggest that functional circuits engage in early, pre-attentive speech perception of either suprasegmental or segmental units in tone languages.

Previous studies also demonstrated that Mismatch Negativity (MMN) was elicited by both stimulus duration increments and decrements (Jaramillo *et al*., 1990; Naatanen *et al*., 1989). MMN generally increased as a function of the degree of discrepancy from the standard-stimulus duration. Nonetheless, the fact that the MMN was still elicited by such an extremely brief sound suggests that the MMN generator is indeed sensitive to even very small amounts of stimulus energy. Consequently, the finding that the MMN amplitude increases as a function of discrepancy in duration and tone change from the standard suggests that the MMN is generated by a process which is a neural code of the degree of stimulus change and accord with results from similar paradigms using other features (Naatanen *et al*., 1989). The propose of the present study was to use both an auditory MMN component of Event-related Potential (ERP) recording and the Low Resolution Electromagnetic Tomography (LORETA) techniques to measure the degree of cortical activation and to localize the brain area contributing to the scalp recorded auditory MMN component, respectively, during the passive oddball paradigm. Thus, the degree of cortical activation in different vowel duration with level-to-contour tone changes were investigated in monosyllabic Thai words.

MATERIALS AND METHODS

Subjects: Twenty-two healthy right-handed adults with normal hearing and no known neurological disorders volunteered for participation: 11 Native Speakers (NS), aged 23-39 (mean 29.7; 9 females) and 11 Nonnative Speakers (NonS), aged 23-29 (mean 25.8; 7 females). The approval of the institutional committee on human research and written consent from each subject were obtained.

Stimuli and procedure: Stimuli consisted of four pairs of monosyllabic Thai words. Speech stimuli were digitally generated and edited to have equal peak energy level in decibels SPL with the remaining data within each of the stimuli scaled accordingly using the Cool Edit Pro v. 2.0 (Syntrillium Software Corporation). The sound pressure levels of speech stimuli were then measured at the output of the earphones (E-A-RTONE 3A, 50 Ω) in dBA using a Brüel and Kjaer 2230 sound-level meter. Three different stimuli were synthetically generated as follows:

- **Stimulus 1:** /k^{h}aam/-long vowel, level tone
- **Stimulus 2:** /k^{h}am/-short vowel, falling tone
- **Stimulus 3:** /k^{h}am/-short vowel, rising tone

The vowel-duration difference between stimulus (1) and (2) was 128 msec (628 vs. 500 msec) and between stimulus (1) and (3) was 89 msec (628 vs. 539 msec) with the same intensity used in each stimulus. Five NS listened to the synthesized words and evaluated them all as natural sounding.

The standard (S)/deviant (D) pairs for each experiment which was randomized across subjects, were shown as follows:

- **Experiment 1:** Standard (1)-Deviant (2)
- **Experiment 2:** Standard (2)-Deviant (1)
- **Experiment 3:** Standard (1)-Deviant (3)
- **Experiment 4:** Standard (3)-Deviant (1)

The sounds were presented binaurally via headphones (Telephonic TDH-39-P) at 85 dB. The Inter-stimulus Interval (ISI) was 1.25 sec (offset-onset). Deviant stimuli appeared randomly among the standards at 10% probability. Each experiment included 125 trials (10% D). The stimuli were binaurally delivered using SuperLab software (Cedrus Corporation, San Pedro, USA) via headphones (Telephonic TDH-39-P). Electro Encephalographic (EEG) signal recording was time-locked to the onset of a word. Subjects were instructed not to pay attention to the stimuli presented via headphones but rather to concentrate on a self-selected silent, subtitled movie.

Electroencephalographic recording: For EEG/ERP recording, the standard 20 locations of the 10-20 system, EEG is recorded via an Electro-cap (Electrocap International) from 20 active electrodes (Fp1, Fp2, F7, F3, Fz, F4, T3, C3, Cz, C4, T4, T5, P3, Pz, P4, T6, O1, Oz, O2) positioned according to the 10-20 International System of Electrode Placement, plus Oz and Ground are applied, pre-mounted in an elastic Electro-Cap. Reference electrodes are manually applied to left and right mandibles, where the Fp1 and Fp2 electrodes are used for ocular artifact detection. Horizontal eye movements are monitored with electrodes at the left and right outer canthi and vertical eye movements are monitored at Fp1 and Fp2. EEG is amplified with a gain of 30,000 and filtered with a bandpass of 0.1-30 Hz. EEGs are acquired as continuous signals and are subsequently segmented into epochs of 1 sec (a 100 msec pre-stimulus baseline and a 900 msec post-stimulus epoch).

EEG data processing: The recordings were filtered and carefully inspected for eye movement and muscle artifacts. ERPs were obtained by averaging epoch which started 100 msec before the stimulus onset and ended 900 msec thereafter, the-100-0 msec interval was used as a baseline. Epochs with voltage variation exceeding ±100 µV at any EEG channel were rejected from further analysis. The MMN was obtained by subtracting the response to the standard from that to the deviant stimulus. All responses were recalculated offline against average reference for further analysis.

Spatial analysis: The average MMN latency was defined as a moment of the global field power with an epoch of 40 msec time window related stable scalp-potential topography (Pascual-Marqui *et al*., 1994). Low-resolution Electromagnetic Tomography (LORETA) was applied to estimate the current source density distribution in the brain which contributes to the electrical scalp field (Pascual-Marqui *et al*., 1994). Maps were computed with LORETA. LORETA computed the smoothest of all possible source configurations throughout the brain volume by minimizing the total squared Laplacian of source strengths.

Data analysis: During the auditory stimulation, electric activity of the subjects' brain was continuously recorded. The MMN was obtained by subtracting the response to the standard from that to the deviant stimulus. The statistical significance of MMN was tested with one sample t-test. An across-experiment ANOVA was carried out so as to make cross-linguistic comparisons.

RESULTS AND DISCUSSION

The grand-averaged ERPs show that both level-to-contour and contour-to-level tone changes perception elicited MMN between 196-220 msec with reference to the standard-stimulus ERPs. The long-to-short duration change with level-to-falling/rising and falling/rising-to-level tone changes perception elicited MMN between 196-220 msec with reference to the standard-stimulus ERPs. The long-to-short duration and level-to-falling/rising tone changes elicited a strong MMN bilaterally for both native and nonnative speakers of Thai, unlike short-to-long duration and falling/rising-to-level tone changes. An ANOVA comparing MMN amplitudes of the S and D yield a main effect of conditions in Experiments 1 ($F_{(3, 40)} = 10.58$, $p<0.0001$) and 3 ($F_{(3, 40)} = 13.70$, $p<0.0001$). In Experiment 2 and 4, however, the S-D differences were not significant (e.g., $F_{(3, 40)} = 1.28$, $p = 0.2258$ in Experiment 2, n.s.; $F_{(3, 40)} = 0.19$, $p = 0.8559$ in Experiment 4, n.s., for the main effect of conditions). The result showed that long-

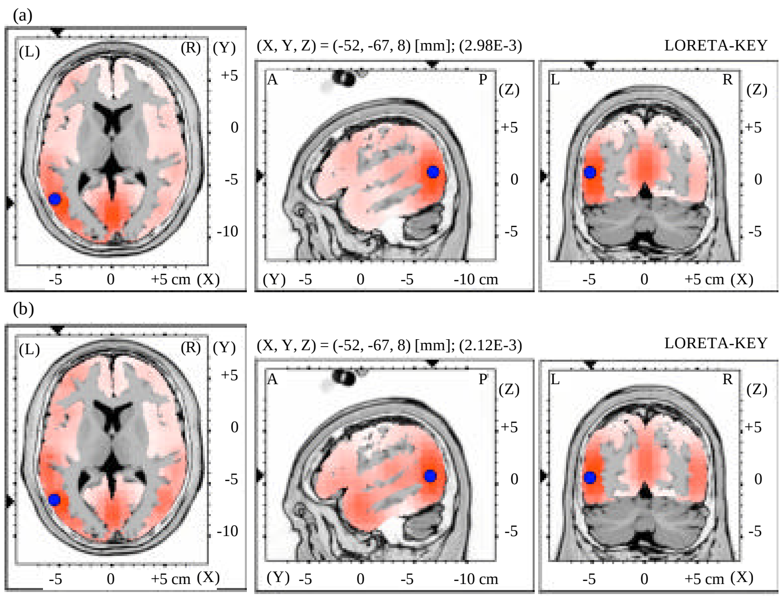

Fig. 1(a-b): Graphical representation of the low-resolution electromagnetic tomography (LORETA) t-statistic comparing the event-related potentials (ERPs) for mismatch negativity (MMN) responses at the time point of the individual peak over Fz for the long-to-short changes of vowel duration with level-to-falling tone, (a) Short-to-long and (b) Changes of vowel duration with falling-to-level tone changes of native speaker (NS) activated in left hemisphere (LH). Red color indicates local maxima of increased electrical activity for across- and within-category of vowel change responses in an axial, a sagittal and a coronal slice through the reference brain. Blue dots mark the center of significantly increased electric activity

Table 1: Mean amplitude (μV)±S.D. of MMN elicited by a vowel duration changes with level-to-contour tones perception in NS and NonS

Vowel duration	NS	NonS
Long (mid)-to-short (falling)	-1.28±0.40	-0.69±0.36
Short (falling)-to-long (mid)	-1.30±0.20	-0.50±0.21
Long (mid)-to-short (rising)	-0.43±0.11	-0.35±0.50
Short (rising)-to-long (mid)	-0.24±0.19	-0.03±0.21

NS: Native speaker, NonS: Nonnative speaker

to-short duration and level-to-falling/rising tone changes elicited a strong MMN bilaterally for NS and NonS, unlike short-to-long duration and falling/rising-to-level tone changes (Table 1). Furthermore, an across-experiment ANOVA demonstrated no interaction and main effects. The significant difference in MMN amplitudes was not observed between groups across experiments ($F_{(7, 80)} = 0.63$, p = 0.6018).

Source localization analyses were performed using LORETA-KEY (Pascual-Marqui *et al*., 1994). Table 2 demonstrates the xyz-values in Talairach space as calculated with LORETA in the time window 196-220 msec. A single source was estimated to be located in the Middle Temporal Gyrus (MTG) of each hemisphere in Experiment 2 and 3 for NS group and in Experiment 1 and 3 for NS group. Sources were obtained in the MTG of the LH and in the Superior Temporal Gyrus (STG) of the RH for NS group in Experiment 1 and 4 and for NonS group in Experiment 2 and 4, respectively (Table 2 and Fig. 1-8).

Table 2: Stereotaxic coordinates of activation foci during the vowel duration changes with level-to-contour tone perception

Vowel duration	BA	Coordinates (mm) x	y	z	t-values
Native Speaker (NS)					
Long (Mid)-to-Short (Falling)	39	-52	-67	8^a	2.98
	22	-53	-60	15^b	2.22
Short (Falling)-to-Long (Mid)	39	-52	-67	8^a	2.12
	37	-53	-60	15^c	2.03
Long (Mid)-to-Short (Rising)	21	-52	-67	8^a	2.27
	37	-53	-60	22^c	2.10
Short (Rising)-to-Long (Mid)	21	-53	-67	8^a	2.08
	22	53	-60	15^b	1.83
Nonnative Speaker (NonS)					
Long (Mid)-to-Short (Falling)	39	-52	-67	8^a	2.03
	22	53	-60	22^a	1.50
Short (Falling)-to-Long (Mid)	21	-52	-67	8^a	1.05
	39	46	-67	8^b	1.22
Long (Mid)-to-Short (Rising)	21	-45	-67	15^a	1.94
	37	53	-60	15^c	1.32
Short (Rising)-to-Long (Mid)	39	-59	-39	1^a	1.18
	22	60	-39	22^b	1.11

BA: Broadmann's area, [a]Left Middle Temporal Gyrus (MTG), [b]Right Superior Temporal Gyrus (STG), [c]Right Middle Temporal Gyrus (MTG)

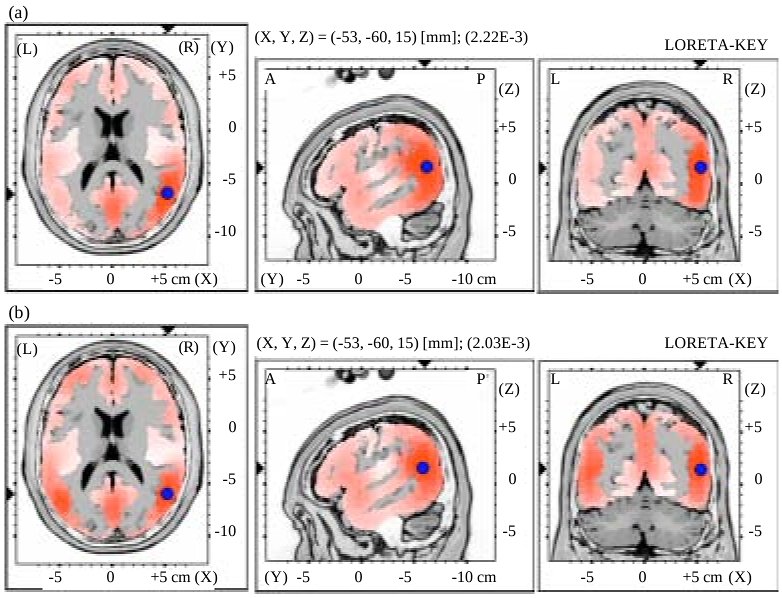

Fig. 2(a-b): Graphical representation of the low-resolution electromagnetic tomography (LORETA t-statistic comparing the event-related potentials (ERPs) for mismatch negativity (MMN) responses at the time point of the individual peak over Fz for the long-to-short vowel duration changes with level-to-falling tone, (a) Short-to-long vowel duration changes with falling-to-level tone and (b) Changes of vowel duration with level-to-falling tone changes of NS activated in RH. More details are shown in Fig. 1

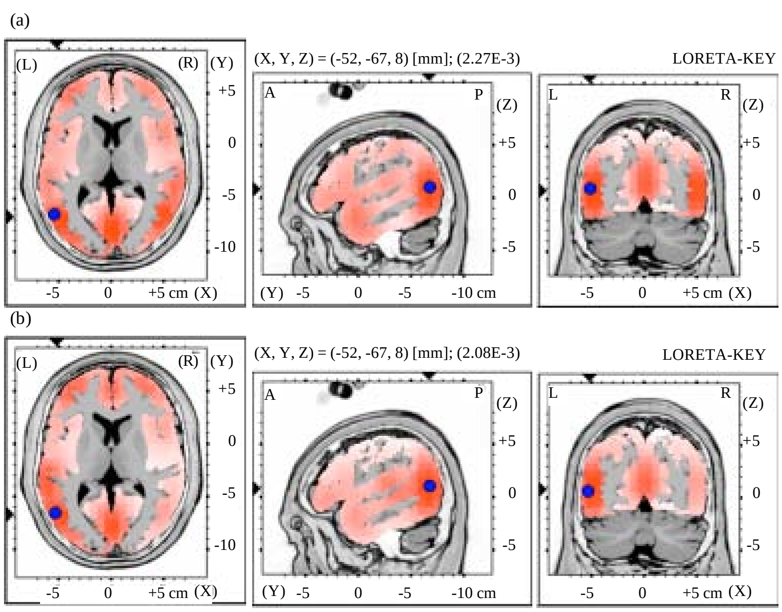

Fig. 3(a-b): Graphical representation of the low-resolution electromagnetic tomography (LORETA t-statistic comparing the event-related potentials (ERPs) for mismatch negativity (MMN) responses at the time point of the individual peak over Fz for the long-to-short vowel duration changes with level-to-rising tone, (a) Short-to-long vowel duration changes with rising-to-level tone and (b) Changes of NS activated in LH. More details are shown in Fig. 1

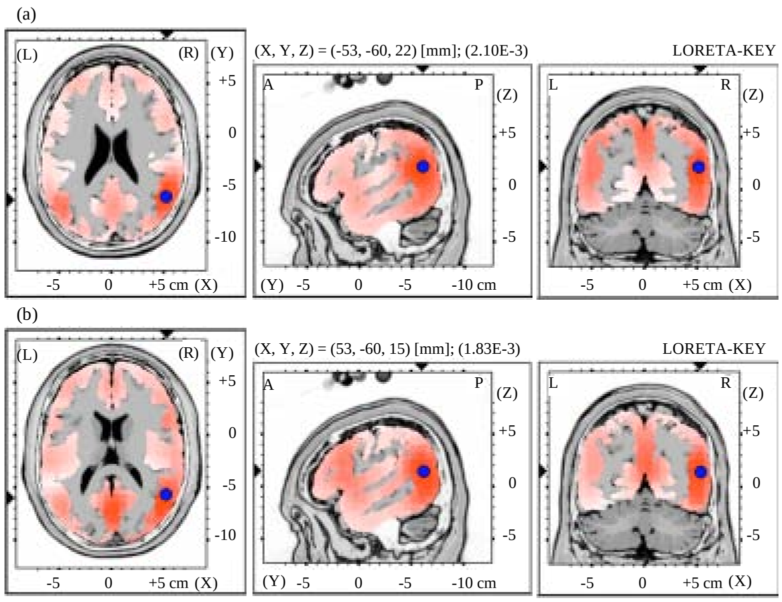

Fig. 4(a-b): Graphical representation of the low-resolution electromagnetic tomography (LORETA t-statistic comparing the event-related potentials (ERPs) for mismatch negativity (MMN) responses at the time point of the individual peak over Fz for the long-to-short vowel duration changes with level-to-rising tone, (a) Short-to-long vowel duration changes with rising-to-level tone and (b) Changes of NS activated in RH. More details are shown in Fig. 1

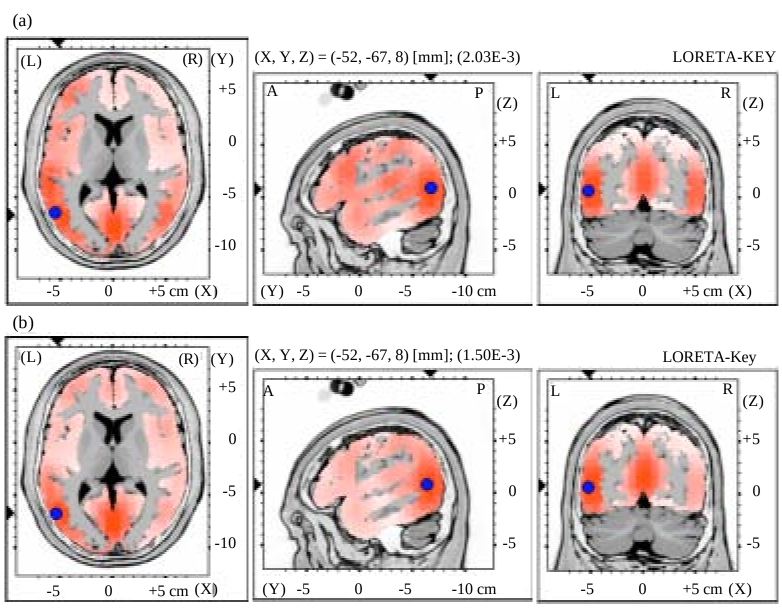

Fig. 5(a-b): Graphical representation of the low-resolution electromagnetic tomography (LORETA t-statistic comparing the event-related potentials (ERPs) for mismatch negativity (MMN) responses at the time point of the individual peak over Fz for the long-to-short vowel duration changes with level-to-falling tone, (a) Short-to-long vowel duration changes with falling-to-level tone and (b) Changes of NonS activated in LH. More details are shown in Fig. 1

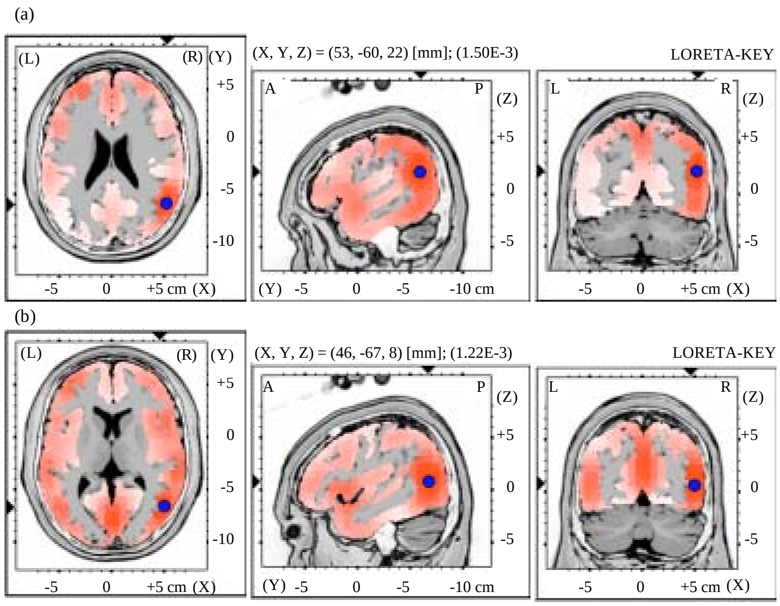

Fig. 6(a-b): Graphical representation of the low-resolution electromagnetic tomography (LORETA t-statistic comparing the event-related potentials (ERPs) for mismatch negativity (MMN) responses at the time point of the individual peak over Fz for the long-to-short vowel duration changes with level-to-falling tone, (a) Short-to-long vowel duration changes with falling-to-level tone and (b) Changes of NonS activated in RH. More details are shown in Fig. 1.

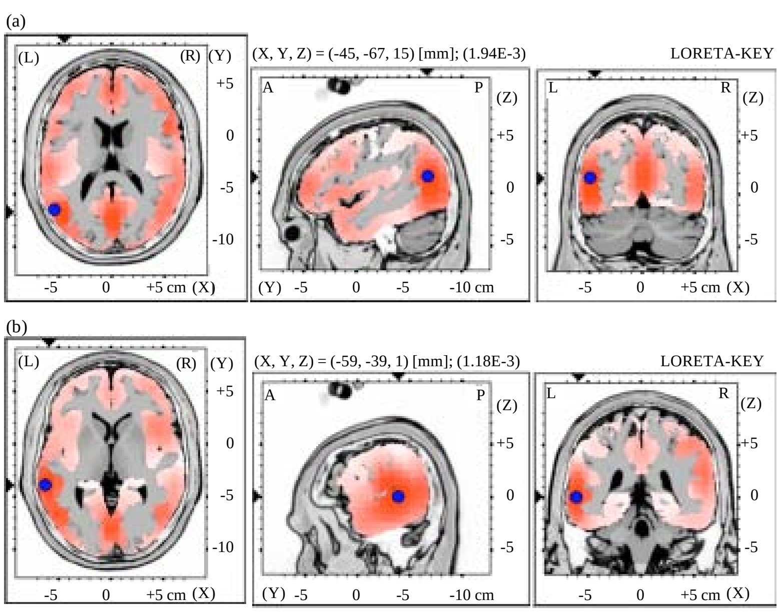

Fig. 7(a-b): Graphical representation of the low-resolution electromagnetic tomography (LORETA t-statistic comparing the event-related potentials (ERPs) for mismatch negativity (MMN) responses at the time point of the individual peak over Fz for the long-to-short vowel duration changes with level-to-rising tone, (a) Short-to-long vowel duration changes with rising-to-level tone and (b) Changes of NonS activated in LH. More details are shown in Fig. 1

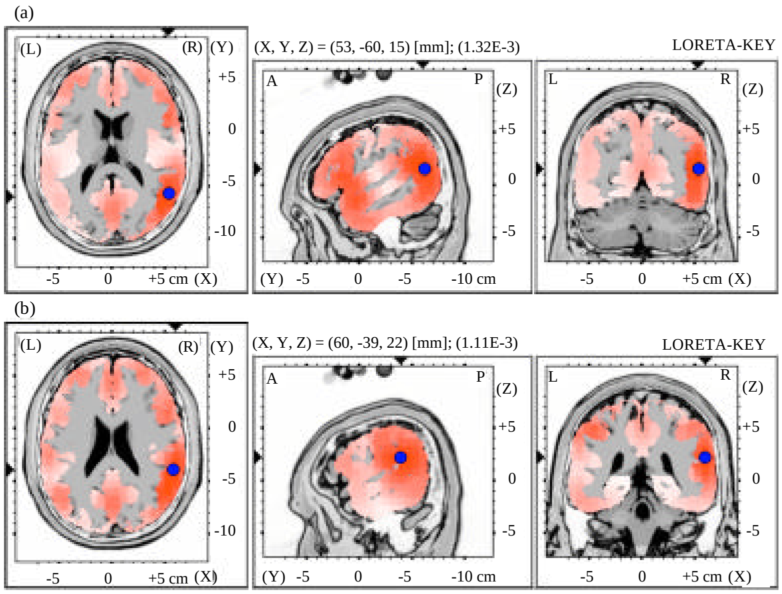

Fig. 8(a-b): Graphical representation of the low-resolution electromagnetic tomography (LORETA t-statistic comparing the event-related potentials (ERPs) for mismatch negativity (MMN) responses at the time point of the individual peak over Fz for the long-to-short vowel duration changes with level-to-rising tone, (a) Short-to-long vowel duration changes with rising-to-level tone and (b) Changes of NonS activated in RH. More details are shown in Fig. 1

The main finding is that for both subject groups, vowel-duration shortening and falling tone elicited prominent MMN components, whereas vowel-duration lengthening and level tone. The same results were obtained in MEG studies using both tone and Japanese words (Inouchi *et al*., 2002, 2003). The present findings are in accord with previous vowel experiment that showed that shortening elicited a larger MMN than lengthening (Jaramillo *et al*., 1990; Inouchi *et al*., 2002). This suggests that at the point of stimulus disparity or thereafter, change detection of vowel lengthening is somehow compromised. It is reasonable to speculate that the continued auditory processing required for the longer vowel interferes with or masks the detection mechanism underlying the MMN (Inouchi *et al*., 2002). In contrast, the current findings contradict previous tone studies that reported a clear MMN elicited by both duration increments and decrements (Inouchi *et al*., 2002) and a larger MMN elicited by increments than decrements (Jaramillo *et al*., 1990). However, the stimulus and presentation between these studies differed considerably; notably the referred to tone study contained stimuli of short durations compared to our longer "word length' stimuli and this might explain the disparity.

The MMN component was also found to be more sensitive to tone falling than rising and leveling for both subject groups. To the extent that both shortening-duration and falling tone conditions reduced acoustic energy in the deviant compared to the standard, similar sensitivity in the MMN was not surprising. The delay in the MMN for falling tone, compared to that of shortening duration, may be due to the incremental spectral deviation, as opposed to the rapid change (omission) in the shortened stimulus (Inouchi *et al*., 2002, 2003). The study confirmed previous results showing that MMN was elicited by both stimulus duration increments and decrements (Jaramillo *et al*., 1990; Naatanen *et al*., 1989; Pascual-Marqui *et al*., 1994). Nonetheless, the fact that the MMN was still elicited by such an extremely brief sound. The MMN generator is indeed sensitive to even very small amounts of stimulus energy. Consequently, the finding that the MMN amplitude increased as a function of discrepancy in duration and tone change from the standard suggests that the MMN is generated by a process which is a neural code of the degree of stimulus change and accord with results from similar paradigms using other features (Naatanen *et al*., 1989).

CONCLUSION

The long-to-short duration with level-to-falling/rising and falling/rising-to-level tone changes perception elicited MMN between 196-220 msec with reference to the standard-stimulus ERPs. The long-to-short duration and level-to-falling/rising tone changes elicited a strong MMN bilaterally for both native and nonnative speakers of Thai, unlike short-to-long duration and falling/rising-to-level tone changes. Source localization analyses performed using LORETA-KEY demonstrates that sources were obtained in the middle temporal gyrus of the left hemisphere and in the superior temporal gyrus of the right hemisphere for both groups.

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