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Index of Long-Term Memory Traces of Vowel Duration Changes: Low-Resolution Electromagnetic Tomography Studies

Wichian Sittiprapaporn
Faculty of Medicine, Mahasarakham University, Maha Sarakham, Thailand

ABSTRACT

Previous studies demonstrated that the processing of a longer vowel was mainly lateralized on the left hemisphere. However, some contradicting evidences employed speech sounds with shorter duration showed that the left hemispheric predominant mismatch negativity (MMN) was not systematically obtained. The main objective of this study is then to use the MMN to provide an index of long-term memory traces for duration of vowel changes with level tone in monosyllabic Thai words. Twenty-two healthy right-handed adults participated in this study. It was found that both long-to-short and short-to-long duration of vowels changes with level tone elicited MMN between 184-208 msec with reference to the standard-stimulus ERPs. The long-to-short duration changes with level tone elicited a strong MMN bilaterally for both native and nonnative speaker of Thai, unlike short-to-long duration change with level tone. The source of long-to-short duration changes was estimated to be located in the middle temporal gyrus of each hemisphere for both groups.

Key words: Event-related potentials, mismatch negativity, sound, vowel, tone

INTRODUCTION

A fundamental, yet controversial issue is whether the human brain contains neural circuits that are uniquely engaged in the early, pre-attentive stage of speech processing. While it seems indisputable that language is subserved by Left-hemisphere (LH) and Right-hemisphere (RH) are lateralized for speech, language or something else. Hypotheses proposed to account for functional hemispheric asymmetries can generally be classified as either cue dependent i.e., basic neural mechanism underlie processing of complex auditory stimuli regardless of linguistic relevance (Ivry and Roberson, 1998; Sittiprapaporn, 2011) or task dependent, i.e., specialized neural mechanisms exist that are activated only by speech (Imaizumi *et al.*, 1998).

Mismatch negativity (MMN), a component of the auditory event-related (ERP), can be used to investigate the neural processing of speech and language (Naatanen and Winkler, 1999; Pulvermuller *et al.*, 2001; Shtyrov *et al.*, 1998, 2000; Naatanen, 1992, 2001; Naatanen *et al.*, 1997; Alho, 1995; Sittiprapaporn *et al.*, 2003, 2005) because it is considered to be a unique indicator of automatic cerebral processing of acoustic stimuli (Shtyrov and Pulvermuller, 2002). MMN, with its major source of activity in the supratemporal auditory cortex, is a brain response elicited in an oddball paradigm where a sequence of repetitive, 'standard', stimuli is interspersed with occasional 'deviant' stimuli that differ from the standard in one or several acoustical or temporal features (Alho, 1995). MMN is thus primarily a response to an acoustic change and an index of sensory memory. Importantly, the MMN can be elicited in the absence of the subject's attention (Naatanen, 1992).

The MMN component appears as a frontocentrally negative wave usually peaking between 100 and 300 msec from the onset of stimulus deviation. The MMN is traditionally thought to reflect the acoustic difference between two sounds, so that the larger the acoustic difference, the faster the behavioral responses of the listeners' and the earlier and larger the MMN. However, if the deviant vowel is near the category boundary, then the familiarity of the stimuli modulates the reaction time (Savela *et al.*, 2003). Moreover, the reaction time results on the speech sound categorization and discrimination demonstrate that vowels were categorically coded (Pisoni, 1973; Polka, 1995).

The present study uses 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 main objective of this study is to use the mismatch negativity (MMN) as indicator to provide an index of experience-dependent and long-term memory traces for duration of vowel changes with level tone in monosyllabic Thai words.

MATERIALS AND METHODS

Participants: Twenty-two healthy right-handed adults with normal hearing and no known neurological disorders volunteered for participation: eleven Native Speakers (NS), aged 18-35 and eleven Nonnative Speakers (NonS), aged 23-35. All participants gave their written informed consent before participation in the study. The age was 24.35 (±4.95) years.

Stimuli and procedure: Stimuli consisted of two 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. Pairs were designed to have similar mid tone. Two different stimuli were synthetically generated:

- **Stimulus 1:** /k^haam/-long vowel, level tone
- **Stimulus 2:** /k^ham/-short vowel, level tone

The vowel-duration difference between stimulus 1 and 2 was 75 msec (628 msec vs. 553 msec) with the same level (mid) tone and 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):** (Stimulus 1: /k^haam/-long vowel, level tone)-(Stimulus 2: /k^ham/-short vowel, level tone)
- **Experiment 2: Standard (2)-Deviant (1):** (Stimulus 2: /k^ham/-short vowel, level tone)-(Stimulus 1: /k^haam/-long vowel, level tone)

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). 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). In the next step, low-resolution electromagnetic tomography (LORETA) is applied to estimate the current source density distribution in the brain which contributes to the electrical scalp field (Pascual-Marqui *et al*., 1994). Maps are computed with LORETA. LORETA computes 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

The grand-averaged ERPs show that both long-to-short and short-to-long duration changes with level tone perception elicited MMN between 184-208 msec with reference to the standard-stimulus ERPs. MMN amplitudes of the S and D was significantly generated a main effect of conditions, as indicated by the t-test comparison between the mean amplitude of MMN at Fz in Experiments 1 ($t(10) = 4.95$, $p = 0.0006$). In Experiment 2, however, the S-D differences were not significant ($t(10) = 0.37$, $p = 7169$, for the main effect of conditions). The result showed that long-to-short duration changes with level tone elicited a strong MMN for NS and NonS, unlike

Table 1: Mean amplitude (μV) ±SD of MMN elicited by a vowel duration changes with level tone perception in NS and NonS

Vowel duration (Level Tones)	Native (NS)	Non-native (NonS)
Long-to-short vowel	-0.57±0.16	-0.81±0.23
Short-to-long vowel	-0.52±0.16	-0.55±0.35

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

	Coordinates (mm)				
Vowel	x	y	z	BA	t-values
Native speaker (NS)					
Long-to-short vowel, level tone	-52	-67	8[a]	39	2.23
	46	-67	8[b]	37	1.14
Short-to-long vowel, level tone	52	-67	8[a]	39	1.26
	53	-60	15[c]	22	1.14
Nonnative speaker (NonS)					
Long-to-short vowel, level tone	-52	-67	8[a]	39	2.52
	46	-67	8[b]	37	1.80
Short-to-long vowel, level tone	-59	-32	15[d]	42	1.26
	60	-32	6[b]	21	1.16

[a]Left Middle temporal gyrus (MTG), [b]Right middle temporal gyrus (MTG), [c]Right superior temporal gyrus (STG), [d]Left superior temporal gyrus (STG), BA: Broadmann area

short-to-long duration change with level tone (Table 1). Furthermore, an across-experiment ANOVA demonstrated an interaction and main effects. The significant difference in MMN amplitudes was observed between groups across experiments ($F_{(3,30)} = 22.92$, $p<0.0001$).

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 184-208 msec. In experiment 1, a single source was estimated to be located in the Middle Temporal Gyrus (MTG) of each hemisphere for both groups. In experiment 2, sources were obtained in the MTG and the Superior Temporal Gyrus (STG) of the right hemisphere for both groups (Table 2, Fig. 1-4).

DISCUSSION

The main findings of the present study show that the duration and tone changes studies show that both long-to-short and short-to-long duration changes with level tone elicited MMN between 184-208 msec with reference to the standard-stimulus ERPs. The long-to-short duration changes with level tone elicited a strong MMN bilaterally for both native and nonnative speaker of Thai, unlike short-to-long duration change with level tone. The xyz-values in Talairach space also show that a source of long-to-short duration changes was estimated to be located in the Middle Temporal Gyrus (MTG) of each hemisphere for both groups.

The results of this study are supported by the MEG studies showing that the processing of a longer vowel (600 msec) was mainly lateralized on the left hemisphere (Eulitz *et al.*, 1995; Polka, 1995; Obleser *et al.*, 2001; Vihla and Salmelin, 2003). However, contradicting evidence was also found in previous reports which employed speech sounds with shorter duration: the left hemispheric predominant MMN was not systematically obtained (Aaltonen *et al.*, 1994; Eulitz *et al.*, 1995; Tervaniemi *et al.*, 1999; Vihla and Salmelin, 2003). It has been proposed that isolated semisynthetic vowels with short duration in a repetitive manner are not processed fully as phonemes in the

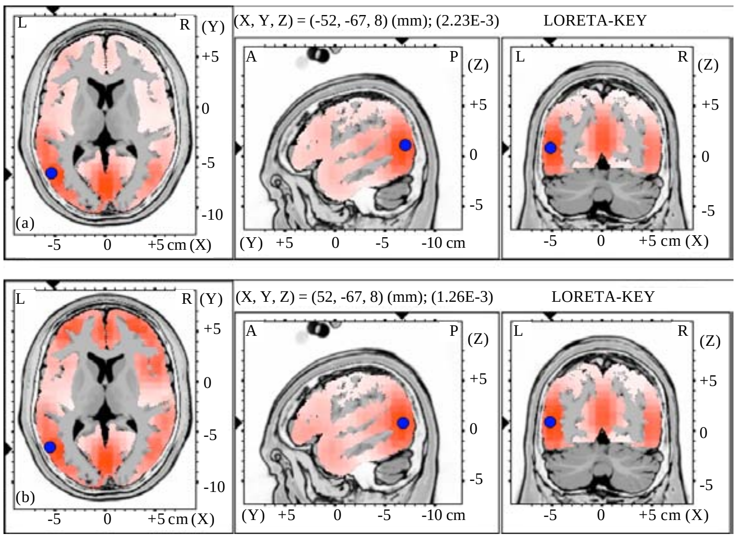

Fig. 1(a-b): Graphical representation of the low-resolution electromagnetic tomography (LORETA t-statistic comparing the event-related potentials for mismatch negativity (MMN) responses at the time point of the individual peak over Fz for (a) Long-to-short duration and (b) Short-to-long duration changes of vowels with level tone 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 saggital and a coronal slice through the reference brain. Blue dots mark the center of significantly increased electric activity

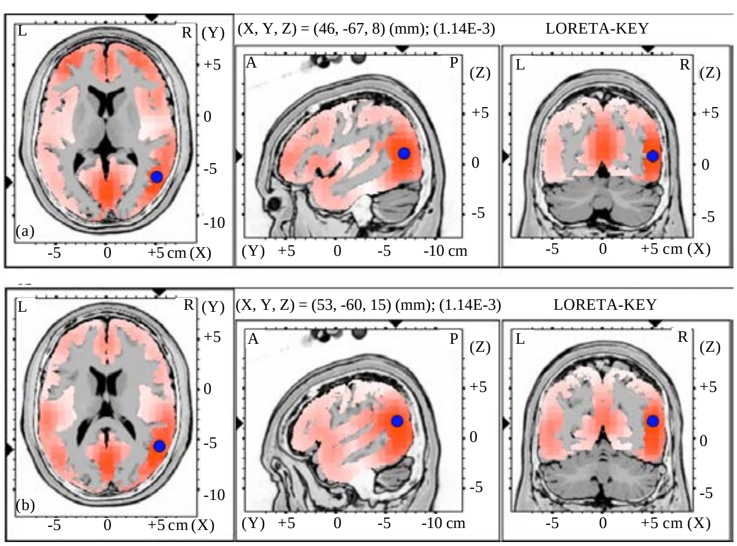

Fig. 2(a-b): Graphical representation of the low-resolution electromagnetic tomography (LORETA t-statistic comparing the event-related potentials for mismatch negativity (MMN) responses at the time point of the individual peak over Fz for (a) Long-to-short duration and (b) Short-to-long duration changes of vowels with level tone of NS activated in right hemisphere, For more details see Fig. 1

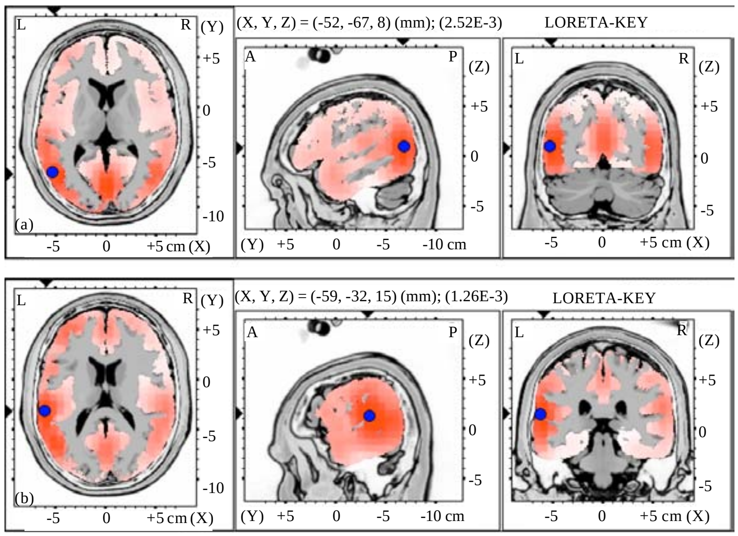

Fig. 3(a-b): Graphical representation of the low-resolution electromagnetic tomography (LORETA t-statistic comparing the event-related potentials for mismatch negativity (MMN) responses at the time point of the individual peak over Fz for (a) Long-to-short duration and (b) Short-to-long duration changes of vowels with level tone of NonS activated in left hemisphere, For more details see Fig. 1

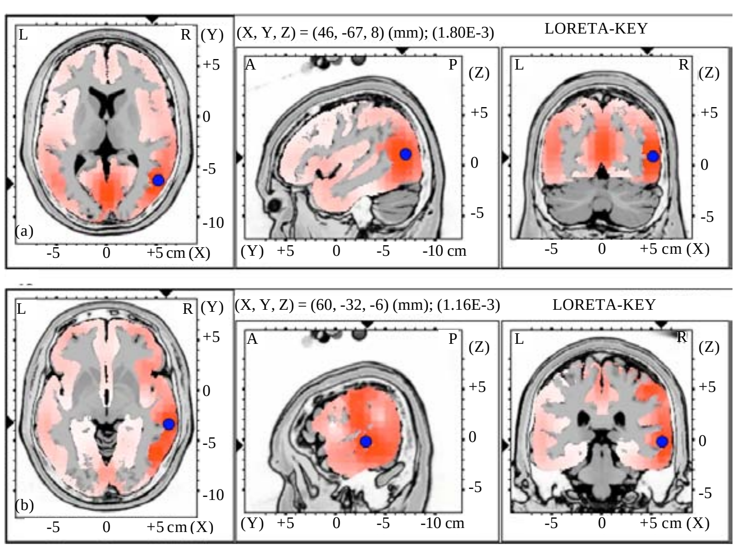

Fig. 4(a-b): Graphical representation of the low-resolution electromagnetic tomography (LORETA t-statistic comparing the event-related potentials for mismatch negativity (MMN) responses at the time point of the individual peak over Fz for (a) Long-to-short duration and (b) Short-to-long duration changes of vowels with level tone of NonS activated in right hemisphere, For more details see Fig. 1

subject's brain (Kasai *et al.*, 2001). Another possible reason for the discrepancy between the present study and previous studies is the naturalness of stimuli. By the use of natural speech of vowel in consonant-vowel syllable, the present data show that the speech-sound naturalness already affects the earlier e.g., preattentive level of speech perception.

The MMN presumably reflect the early stage of speech processing in the human brain. The MMN reflects an early, pre-attentive, automatic speech processing (Naatanen and Winkler, 1999). So, from the known early auditory-cortex responses to sounds, only the mismatch negativity seems to be sensitive to the hemispheric lateralization of the speech function (Shtyrov *et al.*, 1998; Obleser *et al.*, 2001). An advantage of the possible application of MMN as a measure of speech lateralization is that it can be used, unlike behavioral measures, with any subject groups, including patients unable to communicate or concentrate on a test task. The MMN might be of potential interest as a technique of evaluating speech-processing lateralization, since its measurement is non-invasive, relatively inexpensive (especially in case of the EEG) and applicable to any subjects or patients. This should be therefore further studied.

CONCLUSION

Both long-to-short and short-to-long duration of vowels changes with level tone elicited MMN between 184-208 msec with reference to the standard-stimulus ERPs. The long-to-short duration changes with level tone elicited a strong MMN bilaterally for both native and nonnative speaker of Thai, unlike short-to-long duration change with level tone. The source of long-to-short duration changes was estimated to be located in the middle temporal gyrus of each hemisphere for both groups.

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