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Pattern of language-related potential maps in cluster and noncluster initial consonants in consonant-vowel (CV) syllables

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Abstract

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Mismatch negativity (MMN) was used to investigate the processing of cluster and noncluster initial consonants in consonant-vowel syllables in the human brain. The MMN was elicited by either syllable with cluster or noncluster initial consonant, phonetic contrasts being identical in both syllables. Compared to the noncluster consonant, the cluster consonant elicited a more prominent MMN. The MMN to the cluster consonant occurred later than that of the noncluster consonant. The topography of the mismatch responses showed clear left-hemispheric laterality in both syllables. However, the syllable with an initial noncluster consonant stimulus produced MMN maximum over the middle temporal gyrus, whereas maximum of the MMN activated by the syllable with initial cluster consonant was observed over the superior temporal gyrus. We suggest that the MMN component in consonant-vowel syllables is more sensitive to cluster compared to noncluster initial consonants. Spatial and temporal features of the cluster consonant indicate delayed activation of left-lateralized perisylvian cell assemblies that function as cortical memory traces of cluster initial consonant in consonant-vowel syllables.

Key words : EEG, speech perception, auditory cortex, MMN, cluster consonants

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บทคัดย่อ

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ภาพแพนท์สมองด้านภาษาที่แสดงการรับรู้หน่วยเสียงพยัญชนะต้นชนิดควบกล้ำและ
ไม่ควบกล้ำในคำที่มีโครงสร้างพยางค์เดียว
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บทความนี้นำเสนอผลการศึกษาการทำงานของสมองมนุษย์ในการรับรู้หน่วยเสียงพยัญชนะต้นชนิดควบกล้ำและไม่ควบกล้ำในคำโครงสร้างพยางค์เดียวโดยใช้คำที่มีสเมเนกานิกทิวิตี้ (mismatch negativity) จากการศึกษาพบว่าคำที่มีสเมเนกานิกทิวิตี้ตั้งก่อตัว สามารถวัดได้จากการทำงานของสมองในการแยกแยะระหว่างคำโครงสร้างพยางค์เดียวที่เหมือนกัน ยกเว้นหน่วยเสียงพยัญชนะต้นเท่านั้นที่มีความแตกต่างกัน ซึ่งเมื่อได้ทำการเรียบเรียงกับหน่วยเสียงพยัญชนะต้นชนิดไม่ควบกล้ำแล้ว ทำให้พบว่าในการรับรู้หน่วยเสียงพยัญชนะต้นชนิดควบกล้ำสมองจะทำงานมากกว่าโดยดูจากคำที่มีสเมเนกานิกทิวิตี้ นอกจากนี้เมื่อทำการถ่ายภาพแพนท์สมองของคำที่มีสเมเนกานิกทิวิตี้ที่สมองทำงานในการรับรู้หน่วยเสียงพยัญชนะต้นดังกล่าว ยังพบว่าบริเวณซึ่งข่ายของสมองเท่านั้นที่ทำงานในการรับรู้คำโครงสร้างพยางค์เดียวที่มีหน่วยเสียงพยัญชนะต้นทั้งสองชนิด แต่การรับรู้ของสมองที่มีต่อหน่วยเสียงพยัญชนะต้นชนิดควบกล้ำนั้นจะปรากฏบริเวณค่อนไปทางด้านบนและด้านหลังมากกว่าหน่วยเสียงพยัญชนะต้นชนิดไม่ควบกล้ำ กล่าวคือสมองจะรับรู้คำโครงสร้างพยางค์เดียวที่มีหน่วยเสียงพยัญชนะต้นชนิดไม่ควบกล้ำบริเวณ middle temporal gyrus (MTG) และในขณะที่คำโครงสร้างพยางค์เดียวที่มีหน่วยเสียงพยัญชนะต้นชนิดควบกล้ำจะปรากฏบริเวณ superior temporal gyrus (STG) ดังนั้น รายงานผลการวิจัยนี้ที่ใช้คำที่มีสเมเนกานิกทิวิตี้เป็นเครื่องชี้วัดการทำงานของสมองทำให้สามารถอธิบายได้ว่ามนุษย์จะใช้สมองในการรับรู้คำโครงสร้างพยางค์เดียวที่มีหน่วยเสียงพยัญชนะต้นชนิดควบกล้ำมากกว่าชนิดไม่ควบกล้ำ นอกจากนี้ยังทำให้ทราบว่าสมองจะใช้เวลาในการรับรู้คำโครงสร้างพยางค์เดียวที่มีหน่วยเสียงพยัญชนะต้นชนิดควบกล้ำที่ช้ามากกว่าคำโครงสร้างพยางค์เดียวที่มีพยัญชนะต้นชนิดไม่ควบกล้ำ

โครงการวิจัยชีววิทยาระบบประสาทและพฤติกรรม สถาบันวิจัยและพัฒนาวิทยาศาสตร์และเทคโนโลยี มหาวิทยาลัยมหิดล ตำบลศาลาฯ อำเภอพุทธมณฑล จังหวัดนนทบุรี 73170

Mismatch negativity (MMN), an index of preattentive processing of perceived sounds, is an event-related potential (ERP) component elicited by rare deviant stimuli within a sequence of repetitive auditory stimuli. The MMN component appears as a frontocentrally negative wave usually peaking between 100 and 300 ms after the onset of stimulus deviation (Näätänen *et al.*, 1978). The MMN/Mismatch negatives field (MMF) component, reflective neuronal correlates of change detection and sound discrimination (Näätänen *et al.*, 2001), is enhanced by acoustic deviances of duration, frequency, or intensity in speech and non-speech (Näätänen *et al.*, 1978). Previous studies have shown that the MMN amplitude is enhanced when the acoustic discrepancy between the stimuli is increased (Näätänen *et al.*, 1978; Jaramillo *et al.*, 2000). However, the status of linguistic significance in the native language also modulates the MMN amplitude, suggesting the participation of permanent memory traces in the generation of the MMN response (Dehaene-Lambertz, 1997; Näätänen *et al.*, 1997; Phillips *et al.*, 2000). Parallel behavioral and MMN studies have shown that MMN amplitude correlates with the accuracy of perceptual discrimination (Lang *et al.*, 1990; Näätänen *et al.*, 1993), thus, MMN provides an objective method for measuring the accuracy of auditory processing (Nenonen *et al.*, 2003).

It is well-known that auditory signals can be differentiated by a variety of factors including temporal information. It is also important to recognize that languages differ in the way they exploit temporal cues (Gandour *et al.*, 2002).

Standard Thai, the official language of Thailand, exhibits a phonological contrast in consonant. Perceptually, duration has been shown to be the primary cue in signaling the contrast between cluster and noncluster consonant phonemes. The phonemic consonant is sometime not predictable from context, but can change the meaning of a word (e.g., /kaang/ 'spread or make wider' vs. /klaang/ 'middle').

Thai consonants are classified into three classes - namely, high, middle, and low consonants - which can affect the syllable tone when functioning as initial sound. The Thai sound system is best described in relationship to the syllable, the tone-bearing unit. A Thai syllable has the maximum shape of C(C)V(V)(C)+Tone. There are twenty consonants in syllable-initial position. Among these, the initial cluster consonants include the labials - pr, pl, phr, and phl; the alveolars - tr, thr; and the velars - kr, kl, khr, khl, khw. Cluster simplification (kl > k, for example) is often a fixed feature in spoken communication. In the present study, we compared preattentive brain processes during the discrimination of cluster and noncluster initial consonants in consonant-vowel syllables. A single pair of consonant-vowel syllables with cluster and noncluster initial consonants was selected to represent ideal exemplars. In spoken communication, the consonant-vowel syllable with cluster initial consonant is usually pronounced as a simplification of the cluster initial consonant. We chose to record and compare the MMN elicited by the consonant-vowel syllables with cluster and noncluster initial consonants, hoping to find evidence for specific brain signatures of cluster and noncluster initial consonant processing. Two questions were examined using this approach: (1) whether the ERP component MMN would index differences in the brain's discrimination of cluster and noncluster initial consonants in consonant-vowel syllables; and (2) whether MMN amplitude and/or latency would reflect acoustic-phonetic or phonemic differences between the rare deviant and the frequent standard stimuli. Additionally, low-resolution electromagnetic tomography analysis (LORETA) was used to locate multiple non-dipolar

sources particularly involved in the discrimination of cluster and noncluster initial consonants within the MMN paradigm. Our purpose was also to determine when and where in the brain different stages of cluster and noncluster consonant discrimination take place, with particular emphasis on comparisons between the right and the left hemispheres.

Materials and Methods

Subjects

Eleven healthy Thai-speaking right-handed adults (eight women and their age range: 23-29 years; handedness assessed according to Oldfield (1971), with normal hearing and no known neurological disorders volunteered for participation. The mean (\pm sd) age was 25.73 (\pm 3.1) years. Approval of the institutional committee on human research and written consent from each subject were obtained prior to data acquisition.

Stimuli and procedure

Two different consonant-vowel syllables were synthetically generated with (1) noncluster initial consonant /k/- as in /kaang/ 'spread or make wider' and (2) cluster initial consonant /kl/- as in /klaang/ 'middle'. All of the stimuli were digitally edited to have an equal maximum energy level in dB suppressor level with the remaining intensity level within each of the stimuli scaled accordingly. The sound pressure levels of stimulus pairs were then measured at the output of headphones using a Brüel and Kjaer 2230 sound level meter. The standard (S)/deviant (D) pairs for each condition were [Condition 1: Cluster-to-noncluster change] Standard/S-(2), Deviant/D-(1), [Condition 2: Non-cluster-to-cluster change] S-(1), D-(2). Thus, in both conditions pairs were designed to contrast noncluster and cluster initial consonants. The stimuli were presented in a passive oddball paradigm. Deviant stimuli appeared randomly among the standards at 10% probability. Each condition included 125 deviants. The stimuli were binaurally delivered using SuperLab software (Cedrus Corporation, San Pedro, CA, USA) via

headphones (Telephonic TDH-39-P). The inter-stimulus interval (ISI) was 1.25 second (offset-onset). 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 movie. Afterwards, they reported the impression of the movie. The experiment lasted 1-2 h, including breaks.

Electroencephalographic recording

The electroencephalogram (EEG) was recorded in a sound-attenuated and electrically shielded room with a Biologic Brain Atlas III system and amplifier using a sampling rate of 128 Hz. During the auditory stimulation, electric activity of each subject's brain was continuously recorded with 21 active electrodes (Fp1/2, F3/4, C3/4, O1/2, F7/8, T3/4, T5/6, P3/4, Fpz, Fz, Cz, Pz, and Oz) positioned according to the International 10/20 System of Electro-cap and referred to linked mastoids. Epochs of -100 to 924 ms from stimulus onset were averaged and digitally filtered (bandpass 1-30 Hz). Epochs contaminated by artifacts exceeding $\pm 100 \mu\text{V}$ at any electrode as well as 10 standards after each deviant were rejected.

EEG data processing

Grand-averaged difference waveforms were calculated by subtracting the S from the D waveforms. For each condition, presence of a prominent MMN was identified by measuring the integrated power amplitudes over the 40-ms time window centered on the MMN peak in the difference waveform. An MMN component was judged prominent if the amplitude difference between S and D within predefined the window was statistically significant. For each subject, the averaged MMN responses contained 125 accepted deviants.

Spatial analysis

The average MMN latency was defined as a moment of the global field power (GFP) with

an epoch of 40-ms time window related stable scalp-potential topography (Lehmann, 1987). The individual momentary potential measures from 21 electrodes at the MMN latency were analyzed with LORETA to determine the MMN source loci (Pascual-Marqui *et al.*, 1994). LORETA calculated the current source density distribution in the brain contributing to the electrical scalp field, at each of 2395 voxels in the gray matter and the hippocampus of a reference brain (MNI 305, Brain Imaging Centre, Montreal Neurological Institute) based on the linear weighted sum of the scalp electric potentials (Pascual-Marqui *et al.*, 1994). LORETA chooses the smoothest of all possible current density configurations throughout the brain volume by minimizing the total squared Laplacian of source strengths. This procedure only implicates that neighboring voxels should have a maximally similar electrical activity, while no other assumptions are made. The applied version of LORETA used a three-shell spherical head model aligned to the Talairach space, and calculated the three-dimensional localization of the electrical sources contributing to the electrical scalp field for all 11 subjects and conditions, defining the regions of interest (ROI) on the basis of local maxima of the LORETA distribution.

Statistical analysis

The statistical significance of MMN was tested with paired-sample *t*-tests between the MMN amplitude of consonant-vowel syllables with noncluster and cluster initial consonants. This was done by comparing the mean MMN amplitude against a hypothetical zero at the frontal (Fz) electrode site, where the MMN is most prominent. The MMN latency values were also compared.

Results

The results of the grand-mean difference waveform analysis demonstrated that significantly different neuronal populations were active between 128-196 ms when syllables with cluster and noncluster initial consonants were present. The grand-averaged ERPs in Figure 1 show that both

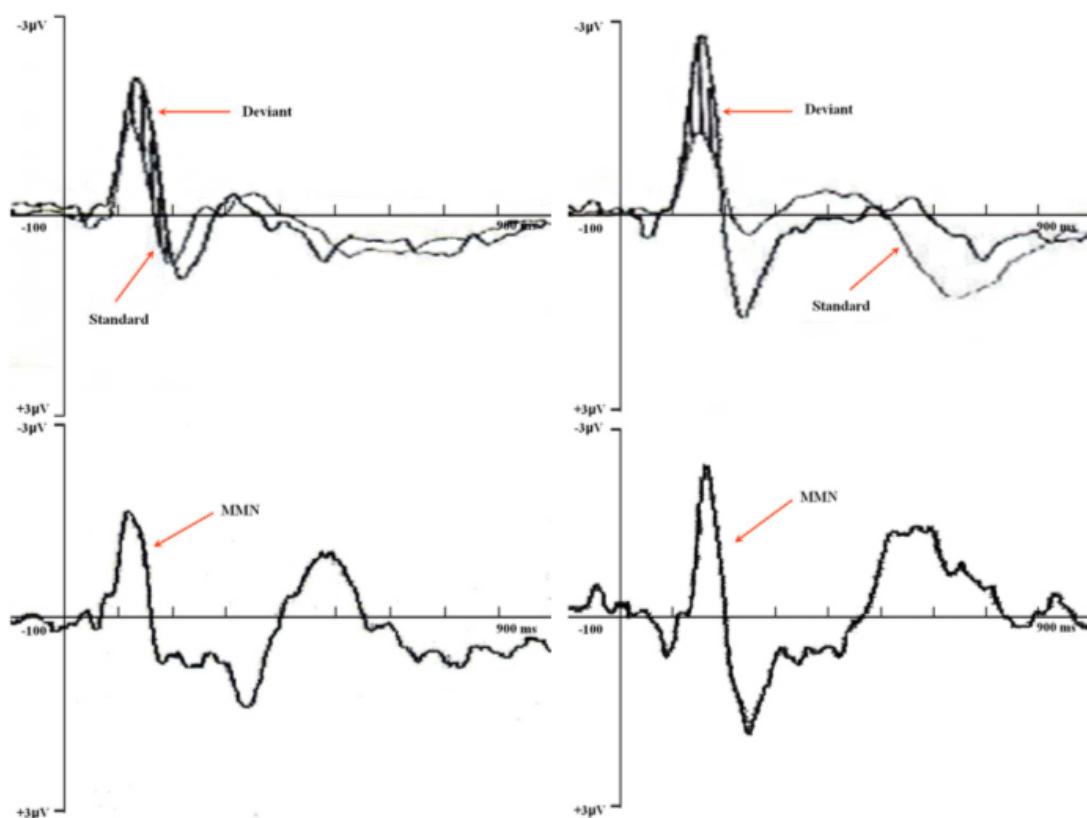


Figure 1. Grand-average ERPs elicited by (Top) standard and deviant stimuli, and (Bottom) deviant-minus-standard difference waves at Fz for syllables with (Left) cluster-to-noncluster initial consonant changes: /kl/-/k/ condition and (Right) noncluster-to-cluster initial consonant changes: /k/-/kl/ condition.

Table 1. The mismatch negativity (MMN) mean amplitude, standard deviations, and *t*-values for the different deviant stimuli used

Consonant changes	Mean MMN Amplitude (μV)	Standard deviation (μV)	<i>t</i>	<i>P</i>
Noncluster-to-cluster	-2.45	0.70	20.95	< 0.0001
Cluster-to-noncluster	-1.95	0.98	4.71	0.0008

cluster- and noncluster initial consonants elicited MMN with reference to the standard-stimulus ERPs. The MMN mean amplitude was statistically significant (*t*-test) for both cluster and noncluster initial consonants changes (Table 1). The paired-sample *t*-test revealed a significant difference between conditions ($t(10) = 73.00; p < 0.0001$)

showing that both cluster and noncluster initial consonants changes in consonant-vowel syllables equally elicited a MMN. The MMN latency for the cluster and noncluster initial consonant differences was significantly longer in the syllable with noncluster-to-cluster initial consonants changes than in the cluster-to-noncluster initial consonants

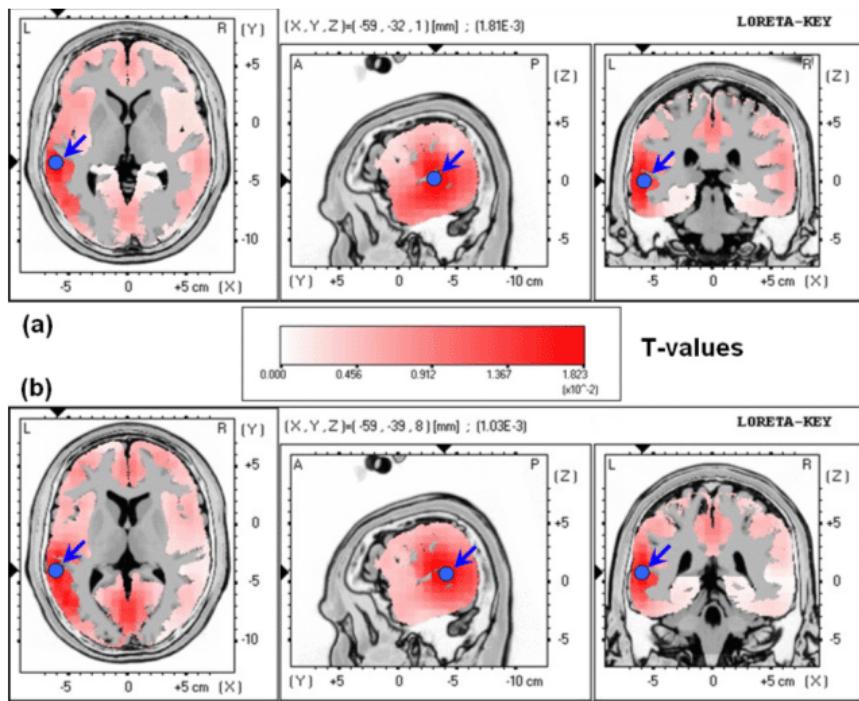


Figure 2. Graphical illustration of the LORETA t-statistic comparing the ERPs for MMN responses at the time point of the individual peak over Fz for syllables with (a) noncluster-to-cluster initial consonants and (b) cluster-to-noncluster initial consonants changes. Red color indicates local maxima of increased electrical activity for cluster and noncluster initial consonant change responses in an axial, a sagittal and a coronal slice through the reference brain. Blue dots mark the center of significantly increased electrical activity.

[Color figure can be viewed in the electronic version]

changes. The strong MMN peaks at ~ 128 ms after change onset in cluster-to-noncluster initial consonants changes and at ~ 196 ms in noncluster-to-cluster initial consonants changes. The significantly different neuronal populations were thus active between 128-196 ms when syllables with cluster and noncluster initial consonants were present (Figure 1).

Estimated source localization of the average MMN responses evoked by cluster and noncluster initial consonants is presented in Figure 2. In this figure, the two estimated source maps are shown for the time-points at the respective MMN peaks (128 ms for the noncluster and 196 ms for the cluster consonants). The source analysis indicated strongest MMN response tentatively originating

in the left hemisphere and possibly involving the perisylvian area in both conditions, with a more superior distribution for the cluster consonant and a more medial distribution for the noncluster consonant.

Table 2 demonstrates the xyz - values of the foci with strongest activation in Talairach space. The current source density values in the time frame 128-196 ms post-stimulus were calculated with LORETA. Stronger activation for noncluster-to-cluster initial consonant changes was found in the left middle temporal gyrus (MTG) (-59, -32, 1; t-value, 1.81), while the cluster-to-noncluster initial consonant changes most strongly activated the left superior temporal gyrus (STG) (-59, -39, 8; t-value, 1.03). Analysis of the MMN responses indicated

Table 2. Stereotaxic coordinates of the strongest activation foci during consonant-vowel syllables with cluster-and noncluster-phoneme-changes of initial consonants discrimination. (BA = Brodmann area)

Consonant changes	BA	Coordinates (mm)			LORETA T-values
		x	y	z	
Noncluster-to-cluster change					
Left middle temporal gyrus	21	-59	-32	1	1.81
Cluster-to-noncluster change					
Left superior temporal gyrus	22	-59	-39	8	1.03

left-hemispheric laterality in both conditions ($F(3,30) = 47.02; p < 0.0001$).

Discussion

The main finding of our study indicates that the prominent response to consonant-vowel syllables with cluster and noncluster initial consonant changes elicited MMN peaking at 128-196 ms from stimulus onset. The magnitude of the acoustic difference between the stimulus pairs was reflected by the MMN amplitude, showing larger MMN amplitudes in consonant-vowel syllable deviants with cluster initial consonants compared to the noncluster consonant. Source analyses indicated strongest MMN responses originating in the left hemisphere, possibly involving the perisylvian area in both conditions with a more temporoparietal distribution. The MMN response to the cluster initial consonant was delayed compared with that for the noncluster consonant, and there was a more temporally distributed MMN to the noncluster consonant than to the cluster one.

The difference in MMN latencies to /kaang/ and /klaang/ may reflect differential processing of syllables with physical differences in their initial consonants. The delay in the MMN to the cluster initial consonant of deviant stimulus i.e. /kl-/ as in /klaang/, may reflect additional time required to process the syllable. This processing apparently involves activation of a memory trace, or cell assembly, which possibly represents the processes of the initial consonant in the syllable. We thus propose that the tuned processing of initial con-

sonant may be caused by the different roles of consonant phonemes in the subjects' native languages. This implies that even if one has two almost closely related phonemes, i.e. cluster and noncluster consonant, fine tuning in the processing of syllable may be inhibited at the pre-attentive level. As it is well established that the MMN amplitude indexes the accuracy of change detection (Näätänen *et al.*, 1978), the larger MMN amplitude to the speech sound change in the present study suggests more accurate sound change detection in syllables with cluster rather than with noncluster initial consonants. Importantly, there was significant difference between exemplar syllables with cluster and noncluster initial consonants, implying that the basic ability to detect speech sound changes in general is on average different in the two initial consonant phonemes.

The electric MMN responses differed significantly between syllables with either cluster or noncluster initial consonant (Figure 2). We found an earlier MMN for the short noncluster consonant stimulus and a delayed MMN for the longer cluster consonant, as well as differential topography of the two responses. The difference in MMN latencies to the two stimuli may reflect differential processing of the syllables. Thus, the delay in the MMN to syllable with cluster initial consonant deviant stimulus may reflect additional time required to process the syllable. This processing apparently involves activation of left-lateralized neural circuitry: the memory trace, or cell assembly, which possibly represents and processes the initial consonant. In other words, the

additional unit, the cluster consonant, could be processed by a separate cortical network of neurons, the activation of which takes more time than the processing of the noncluster consonant.

However, one may argue that the physical differences between syllable stimuli may contribute to the different latencies (and possibly to differential topographies as well). Physically different stimuli usually elicit different evoked potentials, including an early positivity (P1), early negativity (N1) and possibly later responses, and it could therefore be argued that the present results may have been affected by such differences. Regarding this argument, it has been demonstrated that the MMN is known to depend primarily on the magnitude of stimulus contrast (rather than on its direction) (Shtyrov and Pulvermüller, 2002). Therefore, the acoustic difference per se between syllables with the cluster and noncluster initial consonants is unlikely to have confounded the present results. The present results also parallel the findings in previous studies (Inouchi *et al.*, 2002, 2003; Sittiprapaporn *et al.*, 2005) demonstrating that the detection of speech sound changes is most likely acoustically driven rather than semantically driven, such that the stimuli were processed without any access to semantic information. The acoustic aspect in the absence of phonetic or higher-order properties may account for why the syllable with cluster consonant had similar neuronal responses to the noncluster one. The present finding is, thus, in accord with a previous experiment that reported a clear MMN elicited by both increments and decrements of speech sound duration (Näätänen *et al.*, 1989) but a larger MMN elicited by increments than decrements (Jaramillo *et al.*, 1999).

The deviant syllable with noncluster initial consonant elicited an MMN with maximum amplitude at the left middle temporal gyrus (MTG), whereas the cluster consonant MMN was maximal at the left superior temporal gyrus (STG). Source analysis suggested MMN sources to be in the vicinity of the left perisylvian area with a more medial distribution for the noncluster deviant and more superior distribution for the cluster consonant

deviant. It may be that these similar topographies of the neurophysiological brain response do not reflect differential cortical distributions of the underlying neuronal assemblies.

The finding of a significantly left-lateralized electric MMN in the present study supports to the previous study indicating a particularly strong asymmetry between the activated neuronal generators in the two hemispheres (Shtyrov and Pulvermüller, 2002). Additionally, earlier work has also shown that the magnetic counterpart of the MMN, the MMNm, registered in magnetoencephalographic (MEG) experiments, is usually left-lateralized for native-language phonemes and syllables (Näätänen *et al.*, 1997; Alho *et al.*, 1998; Shtyrov *et al.*, 1998, 2000). MMNm responses elicited by spoken words were also found to be left-lateralized in MEG (Pulvermüller *et al.*, 2001; Shtyrov and Pulvermüller, 2002). Therefore, the present left-lateralized electric MMN to the syllables with either cluster or noncluster initial consonants indicates a particularly strong cerebral asymmetry. There are two possible interpretations for this laterality. First, the functional information tied to syllable no matter the type of initial consonant underlies this laterality. As a second possibility, it may be that it is the functional information related to the stimulus contrasts (presence/absence of additional consonant named as 'cluster consonant') that is crucial for the strong involvement of left-hemispheric processes. This would be consistent with earlier findings indicating that the neuronal memory traces of function words and similar lexical items are lateralized more strongly in the cortex compared with other word types (Pulvermüller, 1995; Shtyrov and Pulvermüller, 2002). These results suggest the existence of the long-term memory trace, or cell assembly, representing additional initial consonant named as cluster consonant in syllable and housed primarily in the left hemisphere. Therefore, the MMN response topography and latency may reveal cortical distribution and activity dynamics of these memory traces. However, the present study used only one single pair of consonant-vowel syllables with cluster and noncluster initial consonant as an

exemplar, which imposes certain limitations on generalization of the current results to all cluster initial consonant. Studying this issue using different cluster initial consonant and grammatical forms thus appears to be a fruitful target for further experiments.

Conclusion

The MMN component is more sensitive to consonant-vowel syllables with cluster initial consonant rather than noncluster consonant. Automatic detection of changes in cluster initial consonant consonant-vowel syllable may be a useful index of auditory memory traces of word.

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