ORIGINAL ARTICLE

Long-term memory traces for familiar spoken words in tonal languages as revealed by the Mismatch Negativity

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Abstract

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Mismatch negativity (MMN), a primary response to an acoustic change and an index of sensory memory, was used to investigate the processing of the discrimination between familiar and unfamiliar Consonant-Vowel (CV) speech contrasts. The MMN was elicited by rare familiar words presented among repetitive unfamiliar words. Phonetic and phonological contrasts were identical in all conditions. MMN elicited by the familiar word deviant was larger than that elicited by the unfamiliar word deviant. The presence of syllable contrast did significantly alter the word-elicited MMN in amplitude and scalp voltage field distribution. Thus, our results indicate the existence of word-related MMN enhancement largely independent of the word status of the standard stimulus. This enhancement may reflect the presence of a long-term memory trace for familiar spoken words in tonal languages.

Key words : brain, event-related potential (ERP), human, language, memory trace, Mismatch negativity (MMN), semantics, words

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บทคัดย่อ

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การจดจำระยะยาวของสมองต่อคำที่คุ้นเคยในภาษาพูดที่ใช้วรรณยุกต์ ชี้วัดด้วยค่ามิสแมตช์เนกาทิวิตี้

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มิสแมตช์เนกาทิวิตี้ ซึ่งเป็นค่าที่แสดงการตอบรับทางด้านการรับฟังเสียงของสมองที่มีต่อการเปลี่ยนแปลงทางสัทศาสตร์ของเสียงนำมาใช้ในการศึกษาการทำงานของสมองในการแยกแยะระหว่างเสียงที่คุ้นเคยกับเสียงที่ไม่คุ้นเคย ผลการศึกษาพบว่าค่ามิสแมตช์เนกาทิวิตี้ที่ได้จากหน่วยเสียงของคำที่คุ้นเคยมีค่าสูงกว่าหน่วยเสียงของคำที่ไม่คุ้นเคย ความแตกต่างของพยางค์ทำให้เกิดความแตกต่างในการตอบรับต่อเสียงทั้งในด้านแอมปลิจูดและการกระจายของคลื่นสมองในการตอบรับต่อเสียงอย่างมีนัยสำคัญ ดังนั้น จากการศึกษานี้อาจจะสรุปได้ว่าค่ามิสแมตช์เนกาทิวิตี้ที่สูงแตกต่างกันนั้นอาจเกิดจากการตอบรับของสมองที่แตกต่างกันซึ่งอาจจะบอกได้ว่ามีความจำระยะยาวของคำเกิดขึ้นภายในสมอง

โครงการวิจัยชีววิทยาระบบประสาทและพฤติกรรม สถาบันวิจัยและพัฒนาวิทยาศาสตร์และเทคโนโลยี มหาวิทยาลัยมหิดล ตำบลศาลายา อำเภอพุทธมณฑล จังหวัดนครปฐม 73170

The human voice recognition and discrimination, being amongst the most important functions of the human auditory system, has been recently measured from the electrophysiological activity of the perceiver's brain (Titova and Näätänen, 2001). This was investigated using an objective measure of pre-attentive sound discriminability, called the mismatch negativity (MMN), a component of the auditory event-related potential (ERP) (Näätänen and Alho 1995). The MMN, with its major source of activity in the supratemporal auditory cortex, can be used to investigate the neural processing of speech and language (Näätänen, 2001; Näätänen and Winkler, 1999; Pulvermüller *et al.*, 2001; Shtyrov *et al.*, 2000; Sittiprapaporn *et al.*, 2003; Näätänen, 1999; Näätänen *et al.*, 1997; Alho *et al.*, 1998; Shtyrov *et al.*, 1998). Because it is considered to be a unique indicator of automatic cerebral processing of acoustic stimuli (Shtyrov and Pulvermüller, 2002), the MMN is used to be an indicator to classify the change of phonemes. The MMN is traditionally 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; Picton *et al.*, 2000; Cowan *et al.*, 1993). MMN is thus primarily a response to an acoustic change and an index of sensory memory and can be elicited in the absence of the subject's attention (Näätänen, 1995).

It has recently been found that mismatch negativity in response to individual words is greater than for comparable meaningless word-like (i.e., obeying phonological rules of the language) stimuli (Pulvermüller, 2001) and pseudoword stimuli (Shtyrov and Pulvermüller, 2002). In that study, subjects were presented with word and pseudoword deviant stimuli among pseudoword standards (phonetic contrasts being identical). These earlier studies found an increased MMN to word stimuli (Pulvermüller *et al.*, 2001) distinct in both amplitude and topography from the MMN evoked by pseudoword stimuli (Shtyrov and Pulvermüller, 2002) reflecting the cortical memory traces for words presented among either word or pseudoword standard stimuli. In addition, this enhancement was best explained by the activation of cortical memory traces for words realized as distributed strongly connected populations of neurons (Pulvermüller *et al.*, 2001; Shtyrov and Pulvermüller, 2002; Pulvermüller, 1999; 2001). Even though ones believe that these memory traces have been formed during the subjects' previous language experience (Näätänen, 2001; Shtyrov *et al.*, 2000; Shtyrov and Pulvermüller, 2002; Näätänen, 1999; Pulvermüller 1999; 2001), the others may argue that it was this lexical status difference rather than individual words' memory traces as such which contributed to the larger MMNs to words.

Cross-language studies represent a further step in pursuing the issue of speech-sound memory traces in the human brain. In French speakers carrying out an active task, the MMN was found for a native contrast, but not for a non-native contrast (Dehaene-Lambertz and Dehaene, 1994). On the other hand, the MMN for non-native vowel contrast in Finnish speakers during a passive oddball task was of smaller amplitude despite the physical difference being larger than for the native contrast (Näätänen *et al.*, 1997). It appears that the identification of the deviant as a native-language vowel enhanced the MMN amplitude. It has also been suggested that vowels be retained in the form of auditory memory traces (Studdert-Kennedy, 1980). Consequently, the amplitude of the MMN reflects the activation of permanent speech-sound memory traces in the brain (Näätänen, 2001; Pulvermüller *et al.*, 2001; Näätänen *et al.*, 1997; Dehaene-Lambertz, 1997). These studies already provide some evidence of memory traces, but the answer to questions related to the physiological basis of the processes involved in the discrimination between just perceptibly different stimuli or between non-native consonant-vowel (CV) speech contrasts in tonal languages remains elusive. One common problem of these designs was the use of consonant-vowel (CV) syllables structure, because, in tonal languages, tones are assigned to the prosodic or suprasegmental tier whereas consonants and vowels are assigned to the segmental tier (Gandour *et al.*, 2000). The level of activation on the tone tasks may reflect sensitivity of executive processes to tier representations. We have therefore set out the experiment to extend this issue by demonstrating the existence of memory traces for words in tonal languages from native Thai speakers (NTS) when presented with acoustic-only, native and non-native speech contrasts during a passive oddball paradigm.

Materials and Methods

Subjects

Nine healthy right-handed (handedness assessed according to Oldfield (1971)) volunteers (no left-handed family members, native Thai speakers, aged 18 - 35 years) with normal hearing and no record of neurological diseases were presented with two separate experimental conditions.

Stimuli

Natural speech stimuli of Thai with falling tone /k^hâ/ (IPA System) correspond to the identical tone of Chinese /ta^4/ (PINYIN System), each consisting of consonant-vowel (CV) syllable (monosyllabic word) were prepared: (1) /ta^4/ was used as the standard, and /k^hâ/ as the deviant stimulus; named native condition and (2) the standard stimulus was /k^hâ/ while the deviant was /ta^4/; named non-native condition. All monosyllables in the condition were identical, thus eliminating any effects due to differences in frequency of occurrence of tones. The use of monosyllabic words also eliminated word length effects. Thus, the point where the standard and deviant stimuli differ was in each set at their segmental (i.e., initial consonant) units, which were always /k^h/ and /t/. This means that the acoustic/phonetic contrast between the standard and the deviant stimuli was the same in all two pairs and so was the segmental unit contrast (alveolar vs. velar articulation of the initial consonant, and vice versa). In addition, both standard and deviant stimuli were identical in each set at their suprasegmental (i.e., tone) unit, which was always "falling" tone, and their segmental (i.e., vowel) unit, which was always single vowel /a/. This also means that the standard and deviant stimuli were the same in the suprasegmental (i.e., tone) unit and in the segmental (i.e., vowel) unit. In order to achieve complete similarity in standard-deviant contrasts across stimulus pairs, the pause of about 159 ms after the offset of the phoneme /ta^4/ was generated before the phoneme

/k^{h}â/ plosion because the phoneme /ta^4/ was shorter than /k^{h}â/ (194 ms and 353 ms in duration, respectively). This technique is ideal for the present study, for it allows the recording of separate brain responses to subsequent syllables in continuous speech without component overlap.

Both instrumental analysis and auditory judgment were used to discover the phonological and phonetic realizations of the tones. With regards to an instrumental analysis, it included a combination of both perceptions, judgment on the part of the analyst, and quantitative objective evaluation, established by looking at the pitch traces (Sittiprapaporn *et al*., 1997; 1998). In addition, all of the natural speech stimuli were digitally edited to have equal peak energy level in dB SPL with the remaining data within each of the stimuli scaled accordingly. The fundamental Fo and formant F1 and F2 frequencies of all stimuli were analyzed with the CoolEdit 2000 program (Syntrillium Software Corporation). The sound pressure levels of natural speech stimuli were then measured at the output of the earphones (Telephonic TDH-39-P) in dBA using a Brüel & Kjaer 2230 sound level meter and presented binaurally at a comfortable listening level of ~ 85 dB.

Acoustic Stimulation

In native condition, the native /k^{h}â/ deviant was presented among the non-native /ta^4/ standard, and the reverse was employed in non-native condition. Thus, the standard-deviant acoustic-phonetic contrast, the critical variable determining the MMN (Näätänen and Alho 1997), was identical in all conditions, while the lexical contrasts changed. The two experimental conditions were performed with every subject, their order being counter-balanced across the subject. The stimuli were binaurally delivered at comfortable sound level (determined using the experimental stimuli) through earphones. The stimulus sequence was a block of 500 stimuli which contained randomized sequences of standard stimuli (P = 90%) and deviant stimuli (P = 10%). Both standard and deviant stimuli were 85 dB SPL in intensity. The inter-stimulus interval (ISI) was 1.25 ms (offset-onset). Subjects were instructed to ignore the auditory stimulation by reading books of their choices, which was continued until at least 125 artifact-free ERP trials were collected for each deviant trial.

Electroencephalographic Recording

Subjects were seated in an electrically and acoustically shielded chamber and instructed to read a book of their own choice and to ignore any auditory signals. During the auditory stimulation, electric activity of the subjects' brain was continuously recorded (passband 0.01-100 Hz, sampling rate 128 Hz) with a 20 active electrodes positioned according to the 10-20 International System of Electro-cap and referred to linked earlobes with an electrode between Fz and Fpz connected to ground.

EEG Data Processing

The recordings were later filtered off-line (passband 1-30 Hz). Event-related potentials (ERP) were obtained by averaging epoch, which started 100 ms before the stimulus onset and ended 400 ms thereafter; the - 100 - 0 ms interval was used as a baseline. Epochs with voltage variation exceeding ±100 µV at any EEG channel or at either of the two EOG electrodes were discarded. The MMN was obtained by subtracting the response to the standard from that to the deviant stimulus. For each experiment participant, the averaged MMN responses contained at least 125 accepted deviant trials in each condition. All responses were re-calculated offline against average reference for further analysis.

Statistical Analysis

The statistical significance of MMN (deviant-minus-standard difference) was tested with one-sample t-tests by comparing the mean MMN amplitude at the frontal (Fz) electrode site, where the MMN was most prominent. The MMN was measured using the mean frontal (Fz) amplitude in the 144-204 ms interval of the deviant-minus-standard difference curves. This interval included the grand mean MMN peak latencies in those conditions where MMN was elicited. One sample *t*-tests were used to verify the presence of the MMN component, by comparing the mean amplitude of the 144-204 ms interval against a hypothetical zero, separately in each condition. All results were expressed as mean ± s.e.m. and all significant.

Ethical Considerations

All subjects gave their written informed consent to participate in the experiments and were paid for their participation. The experiments were performed in accordance with the Helsinki Declaration. Ethical permission for the experiments was issued by the Committee on Human Rights Related to Human experimentation (Mahidol University, Thailand).

Results

There was MMN and it was significant in both conditions. The average latency value for both conditions was 174±30 ms. We therefore calculated mean area amplitudes for 30 ms interval around the peak (144-204 ms). The native (/k^hâ/ deviant) condition yielded higher MMN amplitudes than the non-native (/ta^4/ de-viant) condition (respective mean amplitude -2.41 µV and -0.98 µV, respectively, Table 1).

This difference in the MMN amplitude between conditions was highly significant (t (10) = 33.01, d = -1.43 µV, s.e.m. = ±0.04, p<0.0001, two tailed t-test). In addition, analysis of the scalp voltage field distribution of the two responses indicated clear topographical differences between the conditions. As shown in Figure 1, the native (/k^hâ/ deviant) condition was localized in the fronto-central regions whereas the non-native (/ta^4/ deviant) condition exhibited centralized distribution.

Discussion

Our experiment was to extend the findings of the existence of memory traces for spoken words in native speakers of Thai by demonstrating the higher MMNs amplitude to syllables placed in subjects' familiar context than in unfamiliar context, suggesting that the MMNs enhancement is a sign of an activation of neuronal memory traces for spoken word (Pulvermüller *et al*., 2001; Shtyrov and Pulvermüller, 2002). Previous findings have already established that the MMNs enhancement reflects neuronal traces of language sounds, phonemes (Näätänen *et al*., 1997; Dehaene-Lambertz, 1997), word and pseudowords (Pulvermüller *et al*., 2001; Shtyrov and Pulvermüller, 2002). In the present study, MMNs responses were elicited by subjects' familiar context presented among unfamiliar context and vice versa. These results clearly demonstrated that the presence of the subjects' previous linguistic experience on the perception play a major role in amplitude of the MMNs response. The familiar context produced larger MMNs responses from the unfamiliar context in both the amplitude and the scalp voltage field distribution, which localized in the fronto-central regions. The native Thai listeners show the MMN enhancement in the fronto-central regions to the familiar condition

Table 1. Overall MMN Amplitudes Elicited by Deviants.

Condition	Trial type Standard Deviant	Mean MMN amplitude (µV)	*p*
Native	/ta^4/ - /k^hâ/	-2.41 ± 0.04	< 0.0001
Non-native	/k^hâ/ - /ta^4/	-0.98 ± 0.06	< 0.0001

Grand-average frontal (Fz) MMN amplitudes in µV (± S.E.M. - Standard Error of Mean) elicited by deviants measured from the 144-204 ms (Overall MMN) interval. The difference between conditions was tested by two-tailed t-test

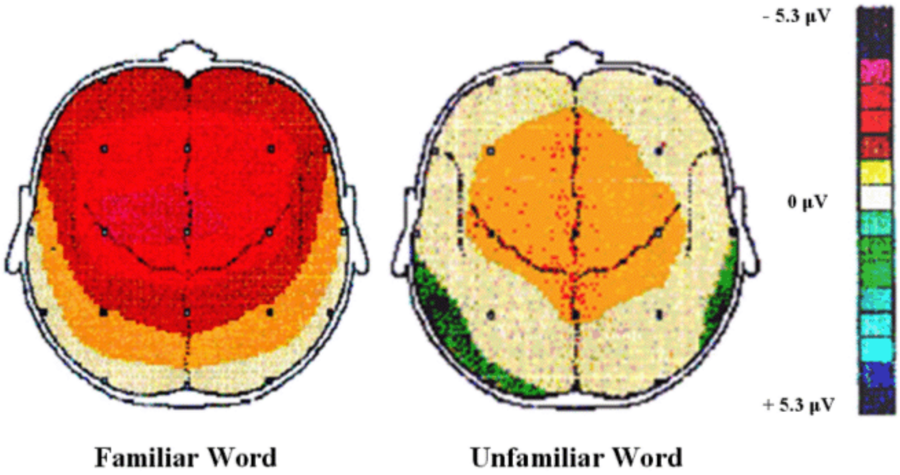

Figure 1. Potential maps of electric MMN responses (deviant-standard subtractions) evoked by deviants measured from the 144-204 ms (overall MMN) interval. Word-elicited MMNs differed in amplitude and scalp voltage distribution from each other.

because pitch variations are perceived by native Thai listeners as phonologically significant at the lexical level in their language. However, when the same Thai listeners are presented with homologous pitch contours in unfamiliar context, they do not show a similar MMN enhancement in fronto-central regions, but in centralized regions. In addition, the MMN enhancement appears to be independent of the syllable status of the standard stimuli. This enhancement is probably caused by the activation of pre-existing long-term memory traces for word stimuli (Shtyrov and Pulvermüller, 2002). These traces, presumably, had been formed during the subjects' previous language experiences (Näätänen, 2001; Shtyrov *et al.*, 2000; Shtyrov and Pulvermüller, 2002; Näätänen, 1999; Pulvermüller, 1999; 2001).

Our findings also suggest that Thai listeners apparently respond to spoken words at the pre-lexical stage of processing, as evidenced by the significant of MMN enhancement on the familiar word condition, compared to the unfamiliar word condition. Spoken words from the subjects' native language elicited a larger neurophysiological mismatch response. This mismatch-response enhancement for words occurred even though subjects were instructed to ignore the word stimuli and focus their attention elsewhere. This enhancement of the mismatch response after word presentation demonstrates the existence of memory traces for words of the subjects' language. It also appears that, at the different linguistic levels, the automatic access to stored language representations leads to the enhancement of the cortical mismatch response (Pulvermüller *et al.*, 2001). Therefore, the significant of MMN enhancement in prelexical perceptual process can be accounted for by the subjects' previous language experience and the degree to which the task is learned or automatic. It is likely that the MMN enhancement is due to a practice effect. In other word, the MMN enhancement to which the familiar condition is engaged in these auditory discrimination tasks reflects different cognitive strategies that native Thai listeners' employ depending on their language experiences. This implies that the brain might be capable of automatic lexical classification of the incoming speech signals already at very early stages of speech processing (Shtyrov *et al.*, 2000; Rinne *et al.*, 1999). This also suggests that auditory parameters of the speech signal are not only encoded in higher cortical areas by their complex acoustic properties (Schwartz and Tallal 1980; Fitch *et al.*, 1997; van Lancker and Sidtis 1992), but also by their linguistic relevance in particular language (Gandour *et al.*, 1998; Liberman and Mattingly, 1989). These findings are corresponding to the views that speech perception simply involves recruiting circuits that already exist for complex auditory analysis. The neural mechanisms underlying the processing of communication sounds and speech perception is thus mediated by unique neural networks in the human brain (Schwartz and Tallal, 1980; Fitch *et al.*, 1997; van Lancker and Sidtis, 1992).

In summary, our results extend to the word-elicited MMN responses and also evidence to earlier studies (Pulvermüller *et al.*, 2001; Shtyrov and Pulvermüller, 2002). These word-elicited MMN responses, presumably, can reflect the presence of the pre-existing long-term memory trace for spoken words of tonal languages. These memory traces for the lexical status of syllable appear to become active as early as 150-200 ms after the word onset. Since the subjects' attention was distracted from the auditory input regarding to the passive oddball paradigm, this possibly implies that the brain might be capable of automatic lexical classification of the incoming speech signals at very early stages of speech processing.

Conclusion

The present results revealed that spoken words from the subjects' native language elicited a larger neurophysiological mismatch response. The existence of the word-related MMN enhancement suggests that the existence of the long-term memory traces might represent spoken words in the human brain. These traces can be activated in the absence of active attention to the auditory input and are probably available at the early stages of cerebral speech processing. Moreover, our findings illustrate how memory and language may interact in phonological processing in different stages of prelexical perceptual process within the fronto-central areas. Therefore, the grand enterprise of pre-existing long-term memory traces for spoken word onto the human brain can be vitally enhanced by mismatch response.

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