ELSEVIER

Cognitive Brain Research 12 (2001) 459–466

COGNITIVE BRAIN RESEARCH

www.elsevier.com/locate/bres

Research report

Are different kinds of acoustic features processed differently for speech and non-speech sounds?

Maria Jaramillo[a], Titta Ilvonen[a], Teija Kujala[a,*], Paavo Alku[b], Mari Tervaniemi[a,d], Kimmo Alho[c]

[a]*Cognitive Brain Research Unit, Department of Psychology, University of Helsinki, PO Box 13, Helsinki FIN-00014, Finland*

[b]*Acoustics Laboratory, Helsinki University of Technology, PO Box 3000, FIN-02015, HUT, Helsinki, Finland*

[c]*Department of Psychology, University of Tampere, FIN-33014, Tampere, Finland*

[d]*Department of Psychology, PO Box 35, University of Jyväskylä, 40351 Jyväskylä, Finland*

Accepted 10 July 2001

Abstract

This study examined how changes in different types of acoustic features are processed in the brain for both speech and non-speech sounds. Event-related potentials (ERPs) were recorded in native Finnish speakers presented with sequences of repetitive vowels (/e/) or complex harmonical tones interspersed with infrequent changes in duration, frequency and either a vowel change (/o/ for vowel sequences) or a double deviant (frequency+duration change for tone sequences). The stimuli were presented monaurally in separate blocks to either the left or right ear. The results showed that speech stimuli were more efficiently processed than harmonical tones as reflected by an enhanced mismatch negativity (MMN) and P3a ERP components. In addition, the duration change in vowels elicited a larger MMN component than the equivalent change in tones. This result might reflect enhanced processing of duration features in the Finnish language in which phoneme duration plays a critical role.

Theme: Neural basis of behavior

Topic: Cognition

Keywords: Speech processing; Temporal change; Mismatch negativity; Change detection

1. Introduction

The issue of whether speech is a special form of auditory input apart from other types of sounds is still being debated. It can be argued on the one hand that speech is simply one type of complex auditory stimuli and is processed in the brain in a similar manner to other types of complex auditory input. On the other hand, it has been proposed that speech is a kind of specialised type of auditory input as distinct from other complex non-speech sounds [17].

One category of acoustic feature that is popularly thought to be relevant to speech is time-related or 'temporal' features. There are several senses in which these temporal features are relevant to speech. Speech is by its very nature sequentially organised (as opposed to the spatial organisation of visual objects) and therefore relies heavily upon temporal attributes. Determining where a word, phrase or sentence ends, for example, are all activities that require temporal processing. Moreover, in certain languages (such as in Finnish), vowel and consonant length are phonemically relevant (i.e. the length of a vowel or consonant determines the meaning of a word). Processing of language and temporal attributes are presumed to be both lateralised to the left hemisphere as suggested by clinical neuropsychological studies [9,33]. Although the left hemisphere dominance for temporal processing was initially demonstrated for very brief time periods (≤200 ms), temporal processing of longer periods (e.g. perception of rhythm of complex sequences that last more than 500 ms) has also been shown to be lateralised to the left hemisphere [25].

*Corresponding author. Tel.: +358-9-191-23760; fax: +358-9-191-22924.

E-mail address: teija.m.kujala@helsinki.fi (T. Kujala).

0926-6410/01/$ – see front matter
PII: S0926-6410(01)00081-7

However, pitch changes may also be important in speech processing in other senses. For example, emotional information is largely transmitted via alterations in pitch contour [3]. Pitch is also phonemically relevant in some tonal languages such as Thai [11]. Processing of pitch changes which convey emotional contours (in contrast to processing of temporal features) appears to be lateralised to the right hemisphere (for a review, see Ref. [4]).

It may be argued that certain kinds of acoustic features are more or less relevant to extracting the speech signal and therefore may be processed differently for speech and non-speech sounds. It is this issue in particular that this study wishes to address. We investigated whether different types of physical features (duration, frequency) were equally discriminated in speech sounds and their non-speech counterparts represented by equally complex tones. The main hypotheses of the present study was that speech stimuli are processed more efficiently than harmonical tones of equal complexity. Monaural stimulation separately for the left and right ear was used in order to primarily stimulate the contralateral hemisphere. This was to find out whether we could detect laterality effects with the present 32-channel EEG recordings in speech processing previously found with other methods [22,26].

We used event-related potentials (ERPs) to measure processing which is not necessarily reliant upon participants' overt and subjective response and additionally, behavioural detection of sound changes in a separate session. One particular index of sound discrimination in the auditory environment that is of interest is the mismatch negativity (MMN) component. It is elicited by any discriminable change in repetitive auditory stimulation (e.g. a change in frequency or duration) and when the physical difference between the standard and deviant stimulus is made larger, then the MMN response becomes larger and earlier [21,28,24]. The fact that the MMN is not obtained with stimuli presented with long intervals without interspersed standard stimuli [18,23,8,14] implies that the repetitive 'standard' stimuli leave a memory trace in the auditory cortex and the deviant stimuli elicit the MMN as a result of the 'mismatch' between the incoming stimulus and the trace of the standard stimulus.

The MMN is also elicited even when attention is directed away from incoming input suggesting that the process underlying MMN elicitation is automatic. These findings have led several theorists to relate MMN to auditory sensory memory [20,6,7,27]. Further, it has been suggested that the MMN reflects a precursor to attention dependent processing (see Refs. [19,20,31,35]). For example, if the stimulus deviance is sufficiently large or novel, a P3a component, which is presumed to relate to involuntary switching of attention, may follow the MMN (for a review, see Ref. [10]).

2. Material and methods

2.1. Subjects

Fourteen healthy Finnish-speaking adults volunteered as participants and gave their informed consent. Three participants' data were discarded from the analyses due to frequent muscle and EOG artifact contamination causing low signal-to-noise ratio in the ERP waveforms. The data of one participant was rejected because after the data collection it was found out that the participant was left-handed. The remaining ten participants with a mean age 24 years (four males) were all right-handed.

2.2. Stimuli and procedure

Stimuli consisted of vowels and harmonical tones which were presented in separate sequences. In the vowel sequences, a frequently presented ($P=0.76$) 'standard' stimulus was the Finnish vowel /e/ (similar in pronunciation to the 'e' in 'bet') was interspersed with three kinds of infrequently occurring 'deviant' stimuli ($P=0.08$): a vowel change to /o/ (as in 'bore'), a frequency change (an /e/ vowel with a higher fundamental frequency) and a duration change (a shorter vowel /e/). The parameters of all the vowel stimuli are given in Table 1. In the harmonical tone sequences, a frequently presented ($P=0.76$) 'standard' stimulus was interspersed with three types of infrequently occurring 'deviant' stimuli ($P=0.08$), a frequency change, duration change and a double (frequency+duration) deviant. This frequency+duration deviant was

Table 1
Stimulus parameters for vowels

Stimulus type	Fundamental frequency (F0) and formants (F1–F10)	Duration (ms)
Standard (/e/)	F0: 105, F1–F10: 470, 2150, 2870, 3500, 4500, 5500, 6500, 7500, 8500, 9500	400
Duration deviant (/e/)	F0: 105, F1–F10: 470, 2150, 2870, 3500, 4500, 5500, 6500, 7500, 8500, 9500	200
Frequency deviant (/e/)	F0: 117, F1–F10: 470, 2150, 2870, 3500, 4500, 5500, 6500, 7500, 8500, 9500	400
Vowel deviant (/o/)	F0: 105, F1–F10: 460, 820, 2470, 3500, 4500, 5500, 6500, 7500, 8500, 9500	400

used both to equate overall deviant probability with the vowel conditions as well as to determine if there was additivity of MMN to the single feature deviants. The harmonical tone stimuli were constructed to match the vowel stimuli in the degree of spectral complexity and the amplitude levels of the harmonic partials were adjusted so that all the partials were half the intensity of the previous partial (e.g. intensity of F2 was half that of F1, . . . , etc.). The frequency and duration of the stimuli were made according to the parameters in Table 2. All stimuli were presented at 65 dB SPL, with 12 ms rise/fall time.

2.3. Procedure

Participants were seated in an acoustically and electrically shielded room and were presented with the stimulus blocks in a random order. Stimuli were delivered monaurally through headphones. There were three blocks of stimulus sequences for all four conditions (left ear vowel, right ear vowel, left ear tone, right ear tone) with each block lasting approximately 9 min. Each stimulus block consisted of 625 stimuli (475 standards and 50 of each deviant type) and the interstimulus (offset to onset) interval was constant at 500 ms. Short breaks were given between blocks and a longer break halfway through the recording session. Participants were instructed to ignore the stimuli while watching a silent, subtitled, self-selected movie on a monitor.

2.4. EEG recording and analysis

EEG was recorded with a 32-channel electrode cap and the electrode positions approximated the international 10-20 system with some additional placements [37]. The reference electrode was attached to the nose. Horizontal eye movements were monitored with electrodes attached to the right and left outer canthi of the eyes and vertical eye movements were monitored using the pre-frontal (Fp1, Fp2, Fpz) electrodes of the cap. The EEG and EOG were amplified with frequency limits (0–40 Hz) and digitised (250 Hz, NeuroScan SynAmp system) online. EEG was then filtered (1.5–30 Hz) offline and epochs of 700 ms (including 100 ms pre-stimulus period) were averaged after artefact rejection (epochs with EEG or EOG exceeding ± 75 μV in any channel). ERPs were averaged separately for each stimulus type. The baseline was set to 0 μV determined as the mean amplitude during the 100-ms prestimulus period. Difference waveforms were calculated by subtracting the ERP to the standard stimulus from the ERP to the corresponding deviant stimulus.

2.5. Behavioural discrimination task

A behavioural discrimination task was always performed after the ERP recording so that the participants remained as naïve of the stimuli as possible in the ERP recordings, and so carry-over effects of attention were avoided. The participants were informed that the sequences consisted of many repetitive standard stimuli, interspersed by three types of deviant stimuli and were then asked to listen to the sound sequences and press a button whenever they heard a deviant sound. The stimuli were identical to those used in the ERP recordings but with fewer trials (a total of 625 stimuli, with 475 standards and 50 of each deviant type for tones and the same number of trials for vowels). Hit rates and reaction time to deviant stimuli were recorded. A response window of 150–1300 ms from the stimulus onset was used.

2.6. Data analysis

Mean amplitudes of ERP components were measured, in reference to the 100 ms baseline, with a 10 ms integration window centered at the group-average peak latency at Fz (for the MMN component) and Cz (for the P3a component) for each condition. One sample *t*-tests were used to determine whether these differed from zero. Multivariate analyses of variance were used to compare amplitudes between conditions. Three different MANOVAs were performed in order to compare the effects both across the stimulus types (tones and vowels) and within the stimulus types (i.e. directly comparing the deviant types). The first MANOVA compared deviant type (duration and frequency), ear (left and right), stimulus type (vowel or tone) and site (left and right hemisphere fronto-central electrodes) as factors. The second MANOVA was a

Table 2
Stimulus parameters for complex tones

Stimulus type	Tone frequencies (Hz) consisting of the fundamental (F0) and its harmonics	Duration (ms)
Standard	F0: 105, Harmonics: 210, 315, 420, 525, 630, 735, 840, 945, 1050, 1155	400
Duration deviant	F0: 105, Harmonics: 210, 315, 420, 525, 630, 735, 840, 945, 1050, 1155	200
Frequency deviant	F0: 117, Harmonics: 234, 351, 468, 585, 702, 819, 936, 1053, 1170, 1287	400
Frequency+duration deviant	F0: 117, Harmonics: 234, 351, 468, 585, 702, 819, 936, 1053, 1170, 1287	200

comparison within the vowels of deviant type (vowel, duration or frequency), site (left and right hemisphere fronto-central electrodes) and ear (i.e. left and right). The third MANOVA was a comparison within the tones of deviant type (dur+freq, duration or frequency), site (left and right hemisphere fronto-central electrodes) and ear (i.e. right and left). Similar analyses were also run on behavioral measures (hit rate and reaction time). Reaction time was measured relative to the onset of the deviation in the deviant stimulus.

3. Results

3.1. ERP data

In all conditions, the deviant-stimulus ERPs were negatively displaced compared to the standard-stimulus ERPs (Fig. 1). This displacement (MMN) is best viewed in the difference waveforms (Fig. 2) and a polarity reversal of this negativity is also visible at the mastoid electrodes (LM, RM), consistent with the known morphology of MMN [1,12,20]. The *t*-tests revealed that mean MMN amplitude was significant ($P<0.05$) in all conditions except for the tone, left ear duration deviant condition (see Tables 3 and 4).

A multivariate ANOVA of mean MMN amplitudes at Fz showed the following effects: The MMN to the vowels were overall significantly larger than the MMNs elicited by the tones ($F_{1,9}=8.9$, $P<0.05$). However, when testing the MMN to the different features in the tones and vowels it was found that the MMN to the duration change in vowels was significantly larger than the MMN to the equivalent duration change in tones ($F_{1,9}=9.8$, $P<0.05$), whereas there was no difference between vowels and tones for the equivalent frequency change. A significant deviant type main effect was also found where the MMN to duration deviant was smaller than that of the frequency+duration or the frequency deviant tones ($F_{2,18}=5.0$, $P<0.05$). A significant deviant type by ear interaction for tones was found, where the MMN amplitudes for left ear stimulation where larger compared to the right ear for frequency or frequency+duration deviants whereas the reverse was true for duration deviants ($F_{2,18}=3.7$, $P<0.05$). No other main effects or interactions were observed in this analysis at Fz. A further ANOVA was performed which examined laterality of MMN at sites placed to the right (F4, F8) and left (F3, F7) sides of Fz. No effects of site or interactions with stimulus type (tone vs. vowel), deviant type or ear were observed in those analyses.

P3a component was significantly elicited by all deviants except the right ear vowel deviant or the left ear frequency deviant in tones (Fig. 2). An ANOVA comparing the P3a mean amplitudes at Cz revealed that the vowels overall elicited a larger P3a compared to the tones ($F_{1,9}=20.3$, $P<0.01$). It also showed that the duration deviants elicited a larger P3a than the frequency deviants across both tones and vowels ($F_{1,9}=5.4$, $P<0.05$). Amongst the vowels, there were significant differences between the deviant types, with the largest P3a being elicited by the duration deviant and the smallest P3a elicited by the vowel deviant ($F_{2,18}=6.1$, $P<0.01$). Amongst the tones, there were no significant differences in P3a amplitudes when comparing ear, deviant type, or their interaction.

In terms of overall morphology, there was no evidence of additivity in the MMN for the frequency+duration deviant and in the MMNs to single feature deviants in the tone condition. However, one can see a second wave emerging in the frequency+duration deviant waveform at a similar time period in which the duration MMN peaked

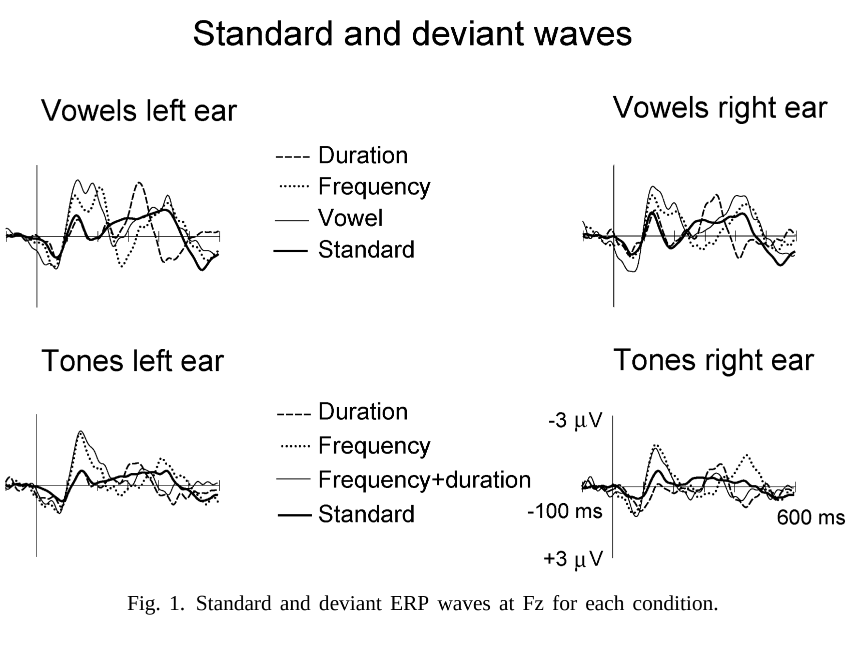

Fig. 1. Standard and deviant ERP waves at Fz for each condition.

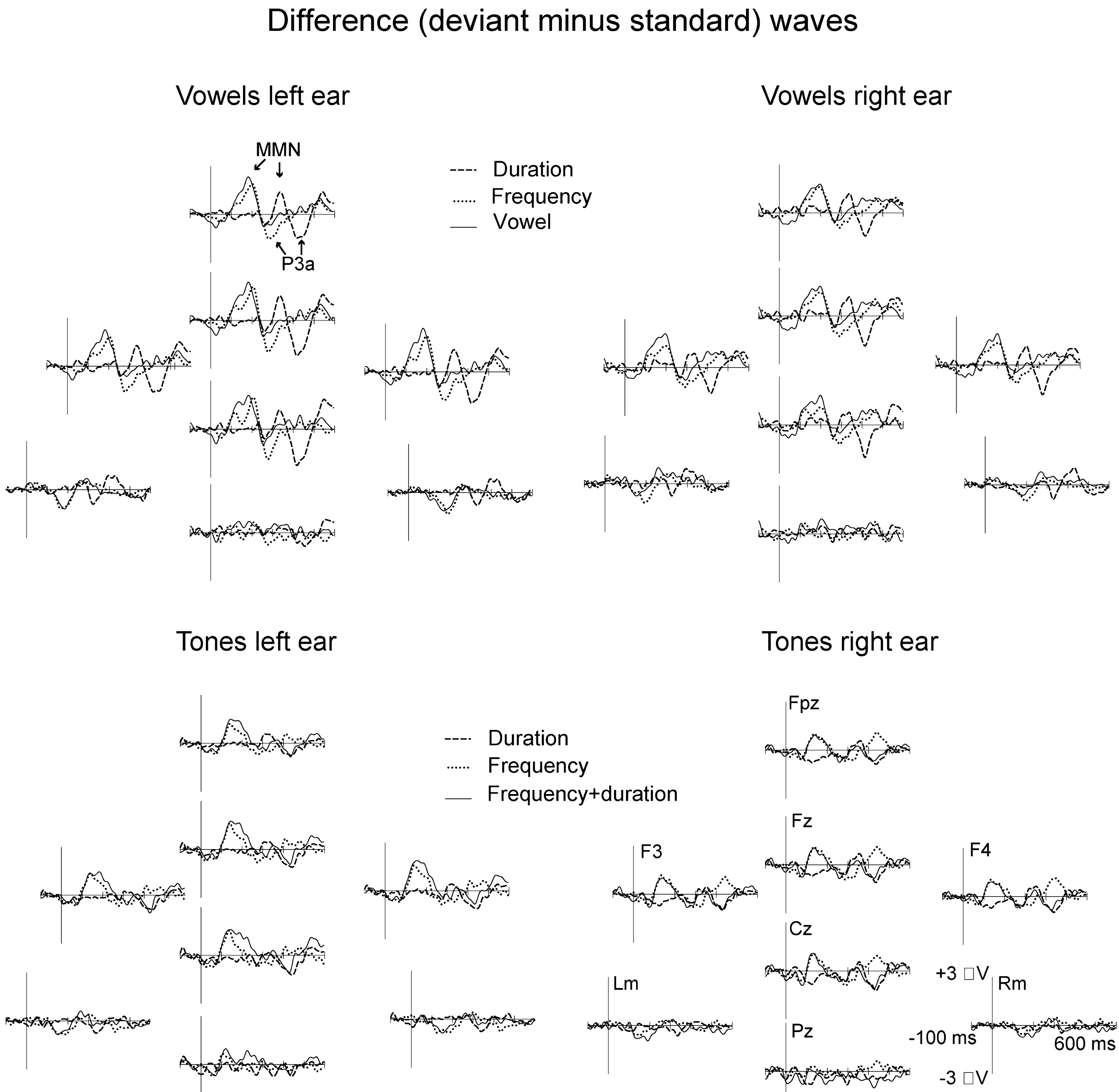

Fig. 2. Difference (the response elicited by the standard stimulus subtracted from the response elicited by the deviant stimulus) ERP waves for each condition at several scalp sites.

(see Fig. 2). This second peak was not significant using t-tests but it is possible that the amplitude may have been suppressed as a result of a positive shift following the earlier large MMN to the frequency deviant in that condition.

There was also a late negative wave in the difference ERP waveforms that was elicited in response to frequency deviants only for the right ear stimulation (mean amplitudes were significant: $t_9=-2.5$, $P<0.05$ and $t_9=-11.3$, $P<0.05$ for the vowel and the tone condition respectively). This late negativity appears to be similar to other late negativities to deviant stimuli observed in other studies at a latency of approximately 300–400 ms, although no clear consensus as to its functional significance has yet been made (see Refs. [2,36,5]).

3.2. Behavioural data

The analysis of hit rate data among the tones showed that the duration deviant tended to be detected less accurately (93.5%) than the frequency+duration (97.14%) or frequency only deviant (97.4%) ($F_{2,18}=3.2$, $P=0.06$).

Table 3
t-tests of MMN mean amplitude for tones

Ear and deviant type	Mean amplitude (μV)	Standard deviation (S.D.)	*t*-value (df=9, *N*=10)	*P*
Left ear, frequency+duration deviant	−1.7	0.8	−6.8	<0.01
Left ear, duration deviant	−0.4	0.9	−1.4	>0.05
Left ear, frequency deviant	−1.6	1.0	−5.4	<0.01
Right ear, frequency+duration deviant	−1.0	1.1	−2.8	<0.05
Right ear, duration deviant	−0.8	0.9	−3.0	<0.05
Right ear, frequency deviant	−1.0	1.1	−3.0	<0.05

For the vowels the duration deviant was also detected less accurately (95.4%) than the frequency deviant (98.2%) or the vowel deviant ($F_{2,18}$=3.7, $P<0.05$). No other main or interaction effects for hit rates were significant, which is likely to be due to a ceiling effect. The mean false alarm rate to standard stimuli was 0.3%, and there were no differences between the false alarm rates for ear or stimulus (tone vs. vowel) types. Analysis of reaction times revealed no significant differences except a difference in reaction times for right and left ear stimuli for vowels, with right ear stimulation yielding a slower reaction time (371 ms) than left ear stimulation (349 ms) ($F_{1,9}$=12.3, $P<$ 0.01).

4. Discussion

The present study examined how different types of physical features in vowels vs. equally complex harmonical tones are processed in the brain. One of our main findings was that the equivalent duration change elicited a larger MMN for the vowel stimuli than for the tonal stimuli. This may suggest that processing of temporal features is more relevant to speech compared to other features and is also consistent with previous findings suggesting that duration changes are processed differently for speech and non-speech sounds [13].

It is possible that this effect relates to the importance of vowel length to the Finnish language. In Finnish, vowel (as well as consonant) length is phonemically relevant. For instance, the Finnish word 'tuuli' means wind and the word 'tuli' means 'fire'. The two words are primarily distinguished by a lengthening in the vowel /u/ and it is likely that this aspect of Finnish language would make any changes in vowel length more easily distinguishable than other types of changes. Although, as acknowledged earlier, it is also possible that differences in durations of phonemes are also important for other reasons (for example determining where a sentence or a word finishes) also in other language groups.

The fact that there were no clear laterality effects in scalp topography as a function of ear of stimulation or deviant type may be attributable to the poor source localization available with the EEG method. Hence, the null results in this respect may reflect the shortcomings of the measures. It is possible that other more precise measures in terms of localization (e.g. MEG or higher resolution EEG combined with realistically-shaped head models) of activity sources would have shown such trends (cf. Refs. [15,26]). It is also possible that the left hemisphere dominance would not be so clear in these speech stimuli since behavioural and laterality studies have shown, for example, that the right ear advantage for speech stimuli is more frequently observed for stop consonants than for vowels [29,32].

The present results also showed that the deviant vowels elicited larger MMNs than the tones. This result may be interpretable within the framework of findings which suggest that native speech contrasts elicit larger MMNs than sounds which do not belong to the native language [22,39]. In addition, stimulus effects were found for the P3as in the present study. The comparison of P3a amplitudes elicited by the deviant tone and vowel stimuli indicated generally larger amplitudes for vowels than for tones. When the P3a amplitudes were analyzed within the conditions it was found that the P3a was larger to the duration as compared with the vowel and the pitch deviant of speech stimuli whereas no amplitude differences were found for the different features of tone stimuli. These results indicate that occasional changes, especially duration

Table 4
t-tests of MMN mean amplitude for vowels

Ear and deviant type	Mean amplitude (μV)	Standard deviation (S.D.)	*t*-value (df=9, *N*=10)	*P*-value
Left ear, duration deviant	−1.5	0.9	−5.7	<0.01
Left ear, frequency deviant	−2.2	1.3	−5.2	<0.01
Left ear, vowel deviant	−2.3	1.0	−7.3	<0.01
Right ear, duration deviant	−1.3	1.0	−4.4	<0.01
Right ear, frequency deviant	−1.7	1.1	−5.0	<0.01
Right ear, vowel deviant	−1.8	1.5	−5.2	<0.01

changes, in speech sounds elicit more easily involuntary attention switches than changes in non-speech sounds.

The behavioral data showed that the duration changes were overall less accurately detected than the other deviant types. However, it is difficult to conclude too much from these data because all deviants were detected at a very high level (mean hit rate was always higher than 92.7% in any given condition) which would indicate a ceiling effect in the behavioral data. A ceiling effect might also have been obtained for the RT data which did not show any differences except between ear of stimulation for vowel stimuli.

Another aspect of the current paradigm is that a double deviant in the tone condition (frequency+duration deviant) was used to assess whether there was additivity of features in the complex tonal stimuli. Several authors [16,30,38,34] have demonstrated that the amplitude of single feature MMNs sum to equal the MMN of the equivalent double feature stimuli. However, when the onset of the two deviations within a double deviant are sufficiently separated in time (at least by 200 ms), then two successive negative waves are elicited by the double deviant instead of one single large additive wave [38]. Our study used a double (frequency+duration) deviant containing two deviations which were separated in their onset by 200 ms, so this latter result would be expected. It was indeed found that there was no single large additive wave for the double deviant, but only a very small second wave emerged within the latency range of the single feature duration change. However, the lack of clear additivity or 'double peaked' MMN for the double deviant may well reflect the very small duration MMN responses in the tones.

In summary, the present data show that duration is processed differently for vowels and tones, but the same is not true for frequency. Moreover, MMN and P3a were larger for speech than for non-speech sounds which may suggest that native speech sounds activate long-term memory traces more easily and readily than unfamiliar sounds. Together these findings suggest that different types of physical changes are not processed equivalently in speech and non-speech sounds.

Acknowledgements

The authors wish to thank Anu Kujala, M.A., and Päivi Sivonen, M.A., for their assistance in piloting the stimuli used in this study. This study was supported by the Academy of Finland.

References

[1] K. Alho, P. Paavilainen, K. Reinikainen, M. Sams, R. Näätänen, Separability of different negative components of the event-related potential associated with auditory stimulus processing, Psychophysiology 23 (1986) 613–623.
[2] K. Alho, D.L. Woods, A. Algazi, R. Näätänen, Intermodal selective attention. II. Effects of attentional load on processing of auditory and visual stimuli in central space, Electroencephalogr. Clin. Neurophysiol. 82 (1992) 356–366.
[3] K. Alter, E. Rank, S.A. Kots, E. Pfeifer, M. Besson, A.D. Friederici, J. Matiasek, On the relations of semantic and acoustic properties of emotions. XIVth International Congress of Phonetic Sciences, 1999, pp. 2121–2124.
[4] A. Basso, Amusia, in: F. Boller, J. Grafman (Eds.), Handbook of Neuropsychology, Vol. 8, Oxford University Press, Oxford, 1993, pp. 373–390.
[5] R. Ceponiene, M. Cheour, R. Näätänen, Interstimulus interval and auditory event-related potentials in children: evidence for multiple generators, Electroencephalogr. Clin. Neurophysiol. 108 (1998) 345–354.
[6] N. Cowan, Attention and Memory: An Integrated Framework, Oxford University Press, New York, 1995.
[7] N. Cowan, Sensory memory and its role in information processing, in: G. Karmos, M. Molnar, V. Csepe, I. Czigler, J.E. Desmedt (Eds.), Perspectives of Event-related Potentials Research (EEG Suppl. 44), Elsevier Science, New York, 1995, pp. 21–31.
[8] N. Cowan, I. Winkler, W. Teder, R. Näätänen, Memory prerequisites of mismatch negativity in the auditory event-related potential (ERP), J. Exp. Psychol. Learn. Mem. Cogn. 19 (1993) 909–921.
[9] R. Efron, Temporal perception, aphasia and deja vu, Brain 86 (1963) 403–424.
[10] C. Escera, K. Alho, E. Schröger, I. Winkler, Involuntary attention and distractibility as evaluated with event-related brain potentials, Audiol. Neurootol. 5 (2000) 151–166.
[11] J. Gandour, D. Wong, G. Hutchins, Pitch processing in the human brain is influenced by language experience, Neuroreport 9 (1998) 2115–2119.
[12] M. Giard, J. Lavikainen, K. Reinikainen, F. Perrin, O. Bertrand, J. Pernier, R. Näätänen, Separate representation of stimulus frequency, intensity, and duration in auditory sensory memory: An event-related potential and dipole-model analysis, J. Cogn. Neurosci. 7 (1995) 133–143.
[13] M. Jaramillo, P. Alku, P. Paavilainen, An event-related potential (ERP) study of duration changes in speech and non-speech sounds, NeuroReport 10 (1999) 3301–3305.
[14] O. Korzyukov, K. Alho, A. Kujala, V. Gumenyuk, R. Ilmoniemi, J. Virtanen, J. Kropotov, R. Näätänen, Electromagnetic responses of the human brain auditory cortex generated by sensory-memory based processing of tone-frequency changes, Neurosci. Lett. 276 (1999) 169–172.
[15] S. Levänen, A. Ahonen, R. Hari, L. McEvoy, M. Sams, Deviant auditory stimuli activate human left and right auditory cortex differently, Cereb. Cortex 6 (1996) 288–296.
[16] S. Levänen, R. Hari, L. McEvoy, M. Sams, Responses of the human auditory cortex to changes in one versus two stimulus features, Exp. Brain Res. 97 (1993) 177–183.
[17] P. Lieberman, Human language and human uniqueness, Language Commun. 14 (1994) 87–95.
[18] R. Näätänen, Neurophysiological basis of the echoic memory as suggested by event-related potentials and magnetoencephalogram, in: F. Klix, H. Hagendorf (Eds.), Human Memory and Cognitive Capabilities, Vol. 1, Elsevier Science Publishers, North Holland, 1986, pp. 615–628.
[19] R. Näätänen, The role of attention in auditory information processing as revealed by event-related potentials and other brain measures of cognitive function, Behav. Brain Sci. 13 (1990) 201–288.
[20] R. Näätänen, Attention and Brain Function, Erlbaum, Hillsdale, NJ, 1992.
[21] R. Näätänen, A.W.K. Gaillard, S. Mantysalo, Early selective attention: effects on the evoked potential reinterpreted, Acta Psychol. 42 (1978) 313–329.
[22] R. Näätänen, A. Lehtokoski, M. Lennes, M. Cheour, M.

Huotilainen, A. Iivonen, M. Vainio, P. Alku, R.J. Ilmoniemi, A. Luuk, J. Allik, J. Sinkkonen, K. Alho, Language-specific phoneme representations revealed by electric and magnetic brain responses, Nature 385 (1997) 432–434.
[23] R. Näätänen, P. Paavilainen, K. Alho, K. Reinikainen, M. Sams, Do event-related potentials reveal the mechanism of the auditory sensory memory in the human brain?, Neurosci. Lett. 98 (1989) 217–221.
[24] R. Näätänen, P. Paavilainen, K. Reinikainen, Do event-related potentials to infrequent decrements in duration of auditory stimuli demonstrate a memory trace in man?, Neurosci. Lett. 107 (1989) 347–352.
[25] M.E.R. Nicholls, Temporal processing asymmetries between the cerebral hemispheres: evidence and implications, Laterality 1 (1996) 97–137.
[26] T. Rinne, K. Alho, P. Alku, M. Holi, J. Sinkkonen, J. Virtanen, O. Bertrand, R. Näätänen, Analysis of speech sounds is left-hemisphere predominant at 100–150 ms after sound onset, NeuroReport 10 (1999) 1113–1117.
[27] W. Ritter, D. Deacon, H. Gomes, D. Javitt, H. Vaughan, The mismatch negativity of event-related potentials as a probe of transient auditory memory: a review, Ear Hear. 16 (1995) 52–67.
[28] M. Sams, P. Paavilainen, K. Alho, R. Näätänen, Auditory frequency discrimination and event-related potentials, Electroencephalogr. Clin. Neurophysiol. 62 (1985) 437–448.
[29] D. Schankweiler, M. Studdert-Kennedy, Identification of consonants and vowels presented to left and right ears, Q. J. Exp. Psychol. 19 (1967) 59–63.
[30] E. Schröger, Processing of auditory deviants with changes in one versus two stimulus dimensions, Psychophysiology 32 (1995) 55–65.
[31] E. Schröger, On the detection of auditory deviations: A pre-attentive activation model, Psychophysiology 34 (1997) 245–257.
[32] T. Spellacy, S. Blumstein, Ear preference for language and non-language sounds: a unilateral function, J. Acoust. Res. 10 (1970) 349–355.
[33] L. Swisher, I.J. Hirsch, Brain damage and the ordering of two temporally successive stimuli, Neuropsyhologia 10 (1972) 137–152.
[34] R. Takegata, P. Paavilainen, R. Näätänen, I. Winkler, Independent processing of changes in auditory single features and feature conjunctions in humans as indexed by the mismatch negativity, Neurosci. Lett. 266 (1999) 109–112.
[35] H. Tiitinen, P. May, K. Reinikainen, R. Näätänen, Attentive novelty detection in humans is governed by pre-attentive sensory memory, Nature 372 (1994) 90–93.
[36] L. Trejo, D. Ryan-Jones, A. Kramer, Attentional modulation of the mismatch negativity elicited by frequency differences between binaurally presented tone bursts, Psychophysiology 32 (1995) 319–328.
[37] J. Virtanen, T. Rinne, R.J. Ilmoniemi, R. Näätänen, MEG-compatible multichannel EEG electrode array, Electroencephalogr. Clin. Neurophysiol. 99 (1996) 568–570.
[38] I. Winkler, I. Czigler, M. Jaramillo, P. Paavilainen, R. Näätänen, Temporal constraints of auditory event synthesis: evidence from ERPs, NeuroReport 9 (1998) 495–499.
[39] I. Winkler, T. Kujala, H. Tiitinen, P. Sivonen, P. Alku, A. Lehtokoski, I. Czigler, V. Csepe, R. Ilmoniemi, R. Näätänen, Brain responses reveal the learning of foreign language phonemes, Psychophysiology 36 (1999) 638–642.