

Short communication

# Activation of the auditory pre-attentive change detection system by tone repetitions with fast stimulation rate

Christian Wolff<sup>a</sup>, Erich Schröger<sup>b,\*</sup>

<sup>a</sup>*Institut für Medizinische Psychologie, Universität München, München, Germany*

<sup>b</sup>*Institut für Allgemeine Psychologie, Universität Leipzig, Seeburgstr. 14–20, D-04103 Leipzig, Germany*

Accepted 13 June 2000

---

## Abstract

The human automatic pre-attentive change detection system indexed by the mismatch negativity (MMN) component of the auditory event-related brain potential is known to be highly adaptive. The present study showed that even infrequent repetitions of tones can elicit MMN, independently of attention, when tones of varying frequency are rapidly presented in an isochronous rhythm. This demonstrates that frequency variation can be extracted as an invariant feature of the acoustic environment revealing the capacity for adaptation of the auditory pre-attentive change detection system. It is argued that this capacity is related to the temporal-window of integration. © 2001 Elsevier Science B.V. All rights reserved.

*Theme:* Neural basis of behavior

*Topic:* Learning and memory: systems and functions

*Keywords:* Auditory event related potential; Mismatch negativity; Pre-attentive change detection; Temporal window of integration

---

Our brain encodes invariant features inherent in recent acoustic input into representations of sensory memory and detects deviations of the current input from this neural model of the constant acoustic environment. This is evidenced by the elicitation of the mismatch negativity (MMN) component of the event-related brain potential (ERP), an indicator of pre-attentive change detection in audition (see e.g. [3,12]; a database for MMN-studies can be found in <http://www.psych.helsinki.fi/cbru/mmn.html>). This neural model encoding the invariances may represent simple features such as frequency, duration, location or intensity of a sound, but also more abstract features such as rules about the succession of elements in tonal patterns consisting of two or more concatenated elements (e.g. [5–16,19,21,23]). For example, Saarinen et al. [10] demonstrated that rarely occurring reversals of the direction of the otherwise constant frequency relation between two tones in a tone pair (ascending or descending) may elicit MMN independently of the absolute frequencies of the tones.

Moreover, also two identical tones when rarely presented in tonal patterns with two (i.e. tone pairs; [10]) or more elements [19,21] usually differing in frequency have been found to elicit MMN. The MMN elicited by tone repetition is interesting for two reasons: First, it creates evidence against the new afferent-elements explanation of MMN, according to which MMN is due to differential states of refractoriness of afferent neurons being sensitive to the features of the Deviant and those of the Standard. Instead, it is evidence for the memory-trace comparison explanation of MMN according to which MMN is elicited if a discrepancy between the representation of the standard sound and that of the current sound is detected. Second, it shows that the representation of the invariances can contain the information that sounds are different against which a representation of a repetition of two identical sounds can be mismatched.

According to the present knowledge about the adaptivity of stimulus representation involved in the pre-attentive change detection system (e.g. [4]) it has to be expected that the pre-attentive detection of a rare repetition of two sounds would not be confined to situations in which this repetition occurs in repetitively presented tonal patterns.

---

\*Corresponding author. Fax: +49-341-9735-969.

E-mail address: [schroger@rz.uni-leipzig.de](mailto:schroger@rz.uni-leipzig.de) (E. Schröger).

One would expect the elicitation of MMN to rare tone repetitions also in isochronous presentation of tones differing in frequency. However, in an experiment reported by Ritter and colleagues [9] occasionally occurring repetition of tones within a series of tones varying in frequency did not elicit MMN. This seems to suggest that tone repetition only elicits MMN when the input is organized into tonal patterns but not when the tones are presented serially one after the other. It would, in turn, imply that frequency variation cannot be extracted as an invariant feature of the acoustic environment in serial presentation of tones, or that tonal repetition cannot be encoded as a feature of the current acoustic input in serial presentation or both. The lack of the ability to establish such representations would define a limit of the adaptivity of the pre-attentive change detection system indexed by MMN.

However, it might be that the absence of MMN to tone repetition is confined to situations with relatively long stimulus-onset asynchronies (e.g. 710 ms as in Ritter's experiment). Indeed, there is evidence from omission studies [20,24,25] and complex tone studies [1,2,12] that a fast stimulation rate may be crucial for eliciting MMN under particular conditions. The present experiment tested the hypothesis that an ongoing variation of tonal frequency in isochronous stimulation may be encoded as the acoustic norm and that infrequent repetitions in the frequency of two successive tones may activate the pre-attentive change detection system indexed by MMN when a fast stimulation rate is used ( $>6$  Hz). That is, tone repetitions were expected to be treated as deviant events — thus eliciting MMN — not only when tone repetitions were task-relevant (Attend Condition) but also when the auditory stimuli can completely be ignored (Ignore Condition).

Twelve paid healthy volunteers (age range 21–40 years, mean 30 years, 10 right-handed, 8 males) reporting normal hearing participated in the experiment. They were seated in a comfortable chair in an acoustically attenuated and electrically shielded cabin. Sinusoidal tones (digitization rate of 35,000 Hz) were generated with NeuroScan stimulation unit and presented binaurally via headphones (Sennheiser HD 450). Each tone had a duration of 60 ms (including 5 ms rise time and 5 ms fall time) and an intensity of 65 dB SPL. In each block 801 tones were presented which could be of one of five different frequencies (700, 800, 900, 1000 or 1100 Hz); each frequency was presented equiprobably; the fixed stimulus-onset asynchrony (SOA) was 160 ms. In 86.25% of the trials the current stimulus (Standard) differed in frequency from the preceding stimulus; in 12.5% of the trials the frequency of the current tone (1-Repitition trial; Deviant) was identical to the frequency of the preceding tone and in 1.25% of the trials the current tone (2-Repitition trial; Deviant) was preceded by two tones of the same frequency. There were two experimental conditions. In the Ignore Condition, including 16 blocks, the subjects were instructed to read a self-selected book and to ignore the auditory stimuli; in the

Attend Condition, including 10 blocks, they were instructed to silently count 2-Repitition stimuli.

The EEG was recorded with NeuroScan data acquisition unit (Synamps amplifier) with Ag–AgCl electrodes from ten scalp locations according to the international 10–20 system: Fpz, Fz, Cz, Pz, F3, F4, FC1, FC2, right (RM) and left (LM) mastoid. The electrodes for the horizontal EOG were placed at the outer canthi of the eyes, the electrodes for the vertical EOG were placed above and below the left eye. Nose served as a reference during recording. The impedance was below 5 k $\Omega$ . The EEG and EOG were continuously recorded and sampled at a rate of 200 Hz and with frequency limits of 0.1 and 40 Hz. The data were analyzed with NeuroScan software: Epochs were 1200 ms in duration (600 ms pre-stimulus and 600 ms post-stimulus), including a 100 ms pre-stimulus baseline. Epochs with EEG or EOG amplitudes exceeding 75  $\mu$ V from baseline were rejected from further analysis. The grand-average ERPs (Fig. 1) were bandpass-filtered between 1 and 30 Hz (24dB/octave). Difference waves were computed (separately for Ignore and Attend Condition) by subtracting the ERPs elicited by the frequent pitch changes (Standards) from the ERPs elicited by 1- or 2-Repitition stimuli (Deviants), respectively. To obtain maximal MMNs the ERPs were re-referenced against the left and right mastoids in the statistical analyses. The presence of the MMN to 1-Repitition stimuli was statistically evaluated by testing the mean amplitudes of the Deviant-Standard difference waves (between 135 and 185 ms after the onset of the 1-Repitition stimulus) at Fz, Cz, Pz, F3, F4, FC1, and FC2 against zero with one-tailed one-group *t*-tests ( $\alpha=0.05$ ).

Distinct MMNs can be seen in both conditions (Fig. 1). All difference waves in the MMN-interval were statistically significant for 1-Repitition stimuli (Table 1). The presence of MMN to tone repetitions in Ignore Condition indicates pre-attentive change detection of the irregular event. This result demonstrates that the frequent change in serial tonal stimulation may be encoded as the standard acoustic background and that infrequent repetitions may be processed as Deviants. This is evidence for a high degree of adaptivity of stimulus representation in pre-attentive change detection. As to be expected on the basis of Ritter's study [9], statistically significant N2b and P3b were elicited by targets (2-Repitition stimuli) in Attend condition.

It has to be asked why tone repetition did not elicit MMN in the experiment by Ritter and colleagues [9], whereas MMN was elicited in the present experiment. The main difference between the two experiments is that the one uses an SOA of 710 ms whereas the SOA was 160 ms in the other one. That is, the time between successive stimuli seems to be the crucial factor being responsible for the difference in the results of both studies. Previous research suggested that a trace build by stimuli with higher order features (e.g. pitch difference between two succes-

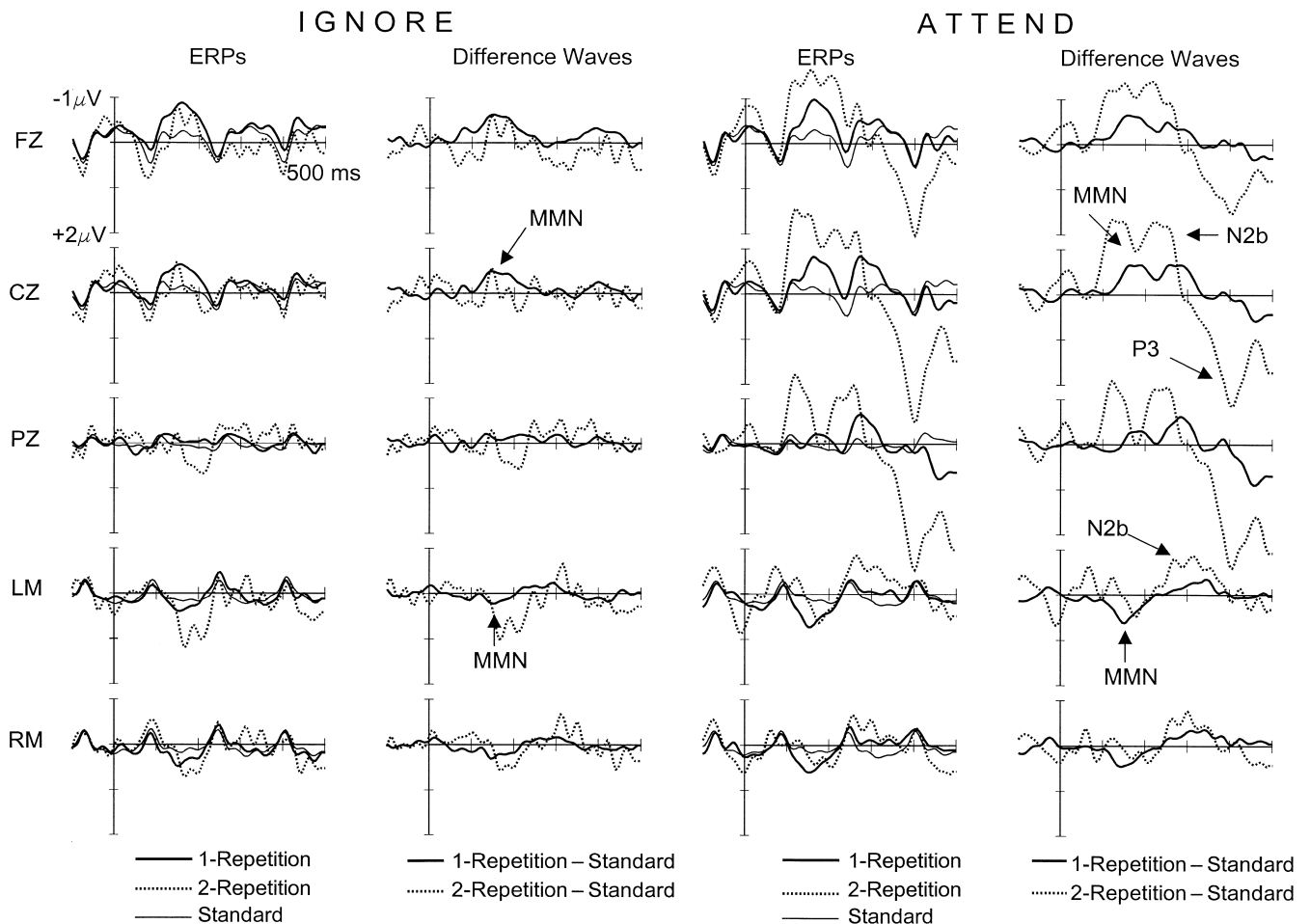


Fig. 1. 1st column: Grand-average ERPs elicited by the standard stimulus, the 1-Repetition and the 2-Repetition Deviants in Ignore Condition; 2nd column: Corresponding Deviant-Standard difference waves. 3rd column: Grand-average ERPs elicited by the standard stimulus, the 1-Repetition and the 2-Repetition Deviants in Attend Condition; 4th column: Corresponding Deviant-Standard difference waves. Brain responses are shown for Fz, Cz, Pz, left and right mastoid (LM and RM, respectively). In both conditions the MMN is visible in the 100–200 ms interval at central leads (negative deflections) and at the mastoids (positive deflections). In Attend Condition N2b occurred between 200 and 300 ms and P3 between 300 and 500 ms to 2-Repetition Deviants.

sive stimuli) is more susceptible to temporal aspects between stimuli, because it represents not a single physical stimulus but a relation of two or more stimuli [1,2,12,20,24,25]. However, when two different physical stimuli fall within the so-called temporal window of integration [4], a sliding window of about 200 ms duration that integrates the acoustic input into a unitary percept, the chunking of the input enabling the establishment of such a relation may be facilitated. Since the acoustic input falling within this window is treated as a unitary event which constituents belong together, the frequency relation between two successive stimuli can be evaluated and a representation about the frequency change can be established. That is, it is an emergent property of the sliding temporal window of integration that two successive stimuli are bound together (and separated from the previous stimuli) so that they can be related to each other. A somewhat similar finding has been reported by Winkler

and co-workers [22] and by Sussmann and co-workers [18] according to which only one MMN is elicited when two successive deviations fall within the temporal window of integration. This suggests that the occurrence of the first deviation must have been taken into account when processing the second deviation within the temporal window of integration.

It should be noted that the co-occurrence of the two successive stimuli within the temporal window of integration is only one way that the input can be organized into units which can be related to each other. The establishment of the representations about relations may also be influenced by the timing of stimulus presentation, yoking stimuli belonging together and separating those which do not belong together. This principle has been utilized in MMN studies where the inter-tone interval within tonal patterns or tone-pairs was smaller than the between-pattern or between-pair interval (e.g. [5–16,19,21,23]). It has to be

Table 1

Mean amplitudes (in  $\mu\text{V}$ ), S.E.M. and  $p$ -value of the MMN waves (between 135 and 185 ms after stimulus onset) obtained with 1-Repetition stimuli in Ignore and Attend Condition. MMN was measured as the mean amplitudes obtained at Fz, Cz, Pz, F3, F4, FC1, and FC2 referred against the mean amplitude of both mastoids

Condition	Deviant	Electrode-position	Mean amplitude ( $\mu\text{V}$ )	S.E.M.	$p$ -value of 1-tailed $t$ -test
Ignore	1-Repetition	FZ	-0.92	0.18	0.000
		CZ	-0.74	0.17	0.001
		PZ	-0.36	0.11	0.004
		F3	-0.80	0.16	0.000
		F4	-0.89	0.18	0.000
		FC1	-0.87	0.17	0.000
		FC2	-0.88	0.18	0.000
Attend	1-Repetition	FZ	-1.16	0.19	0.000
		CZ	-1.13	0.20	0.000
		PZ	-0.68	0.16	0.001
		F3	-1.02	0.15	0.000
		F4	-1.22	0.18	0.000
		FC1	-1.12	0.19	0.000
		FC2	-1.22	0.20	0.000

predicted that other physical features that cause streaming or grouping effects [17] such as location or intensity may serve a similar function.

## Acknowledgements

This research was supported by EU (BMH4-CT96-0819, COBRAIN), the Max-Planck-Institute for Psychological Research (Munich, Germany), and the Deutsche Forschungsgemeinschaft (Schr 375/7-1). The authors thank Monika Fahn, Judith Kallo, Thomas Klass, Verena Pritschow, Sabine Spreer and Renate Tschakert for their help in data acquisition.

## References

- [1] C. Alain, D.L. Woods, K.H. Ogawa, Brain indices of automatic pattern processing, *NeuroReport* 6 (1994) 140–141.
- [2] E.D. Mengler, P.T. Michie, J.H. Hogben, Automatic detection of change in the sequence of events at short inter-stimulus intervals, Poster presented at the 'First International Workshop on Mismatch Negativity and its Clinical Applications', Helsinki, October 1998.
- [3] R. Näätänen, *Attention and Brain Function*, Erlbaum, Hillsdale, NJ, 1992.
- [4] R. Näätänen, I. Winkler, The concept of auditory stimulus representation in cognitive neuroscience, *Psychol. Bull.* 125 (1999) 826–859.
- [5] H. Nordby, W.T. Roth, A. Pfefferbaum, Event-related potentials to breaks in sequences of alternating pitches or inter-stimulus intervals, *Psychophysiology* 25 (1988) 262–268.
- [6] P. Paavilainen, M. Jaramillo, R. Näätänen, Binaural information can converge in abstract memory traces, *Psychophysiology* 35 (1998) 483–487.
- [7] P. Paavilainen, M. Jaramillo, R. Näätänen, I. Winkler, Neuronal populations in the human brain extracting invariant relationships from acoustic variance, *Neurosci. Lett.* 265 (1999) 179–182.
- [8] P. Paavilainen, J. Saarinen, M. Tervaniemi, R. Näätänen, Mismatch negativity to changes in abstract sound features during dichotic listening, *J. Psychophysiol.* 9 (1995) 243–249.
- [9] W. Ritter, P. Paavilainen, J. Lavikainen, K. Reinikainen, K. Alho, M. Sams, R. Näätänen, Event-related potentials to repetition and change of auditory stimuli, *Electroenceph. Clin. Neurophysiol.* 83 (1992) 306–321.
- [10] J. Saarinen, P. Paavilainen, E. Schröger, M. Tervaniemi, R. Näätänen, Representation of abstract attributes of auditory stimuli in the brain, *NeuroReport* 3 (1992) 1149–1151.
- [11] E. Schröger, An event-related potential study of sensory representations of unfamiliar tonal patterns, *Psychophysiology* 31 (1994) 175–181.
- [12] E. Schröger, On the detection of auditory deviations: A pre-attentive activation model, *Psychophysiology* 34 (1997) 245–257.
- [13] E. Schröger, R. Näätänen, P. Paavilainen, Event-related brain potentials reveal how non-attended complex sound patterns are represented by the human brain, *Neurosci. Lett.* 146 (1992) 183–186.
- [14] E. Schröger, P. Paavilainen, R. Näätänen, Mismatch negativity to changes in a continuous tone with regularly varying frequencies, *Electroencephalogr. Clin. Neurophysiol.* 92 (1994) 140–147.
- [15] E. Schröger, M. Tervaniemi, R. Näätänen, Time course of loudness in tone patterns is automatically represented by the human brain, *Neurosci. Lett.* 202 (1995) 117–120.
- [16] E. Schröger, M. Tervaniemi, C. Wolff, R.N. Näätänen, Preattentive periodicity detection in auditory patterns as governed by time and intensity information, *Cogn. Brain Res.* 4 (1996) 145–148.
- [17] E. Sussman, W. Ritter, H.G. Vaughan Jr., An investigation of the auditory streaming effect using event-related brain potentials, *Psychophysiology* 36 (1999) 22–34.
- [18] E. Sussman, I. Winkler, W. Ritter, K. Alho, R. Näätänen, Temporal integration of auditory stimulus deviance as reflected by the mismatch negativity, *Neurosci. Lett.* 264 (1999) 161–164.
- [19] M. Tervaniemi, S. Maury, R. Näätänen, Neural representations of abstract stimulus features in the human brain as reflected by the mismatch negativity, *NeuroReport* 5 (1994) 844–846.
- [20] M. Tervaniemi, J. Saarinen, P. Paavilainen, N. Danilova, R. Näätänen, Temporal integration of auditory information in sensory memory as reflected by the mismatch negativity, *Biol. Psychol.* 38 (1994) 157–167.
- [21] M. Tervaniemi, E. Schröger, R. Näätänen, Pre-attentive processing

- of spectrally complex sounds with asynchronous onsets: an event-related potential study with human subjects, *Neurosci. Lett.* 227 (1997) 197–200.
- [22] I. Winkler, I. Czigler, M. Jaramillo, P. Paavilainen, R. Näätänen, Temporal constraints of auditory event synthesis: evidence from ERPs, *NeuroReport* 9 (1998) 495–499.
- [23] I. Winkler, E. Schröger, Storing temporal features of complex sound patterns in auditory sensory memory, *NeuroReport* 6 (1995) 690–694.
- [24] H. Yabe, M. Tervaniemi, K. Reinikainen, R. Näätänen, Temporal window of integration revealed by MMN to sound omission, *NeuroReport* 8 (1997) 1971–1974.
- [25] H. Yabe, M. Tervaniemi, J. Sinkkonen, M. Houttilainen, R.J. Ilmoniemi, R. Näätänen, Temporal window of integration of auditory information in the human brain, *Psychophysiology* 35 (1998) 615–619.