

# The Mismatch Negativity: A Powerful Tool for Cognitive Neuroscience

Risto Näätänen

**This article reviews research on the relatively recently discovered event-related potential component, the mismatch negativity (MMN), which is of great potential interest for understanding central auditory function and various forms of its pathology. This change-specific response can serve as an accurate objective measure for central sound representations that form the basis, for instance, for correct hearing of speech. Deficiencies in the MMN may be related to different forms of deficits in central auditory processing.**

(*Ear & Hearing* 1995;16:6–18)

In this article, the mismatch-negativity (MMN) component of the auditory event-related potential (ERP) will be reviewed in order to highlight its potential application to research on audition and auditory physiology as well as to suggest possible uses in clinical audiology. The MMN is obtained by presenting the subject or patient with a block of several hundred identical stimuli ("standards"), which are occasionally replaced by acoustically deviant stimuli, and thereafter subtracting the response elicited by standards from that elicited by the deviants. This difference wave shows a negativity that, depending on the magnitude of stimulus deviation, peaks at 100 to 200 msec after stimulus onset (Fig. 1). This negativity is generated by a change-discrimination process that mainly occurs in auditory cortex. Several features make this response a specially attractive tool for auditory research and clinical practice.

1) The MMN is elicited by any discriminable change of a repetitive sound and can be elicited by stimulus differences that approximate the behavioral discrimination threshold.

2) The MMN provides an objective measure of individual discrimination ability for different simple and complex (such as phonemic) sound features.

3) Because it can be elicited without attention, the MMN is free from attentional variations that contaminate behavioral measures and attention-dependent physiological measures of auditory function. In addition, auditory function can be studied even in individuals unable or unwilling to cooperate.

4) Because central auditory representations (short-term sensory memory in audition) are involved in MMN generation (the deviant stimulus acting as a probe for these representations), the MMN provides a unique window to view the neurophysiological processes underlying normal hearing. These representations are physiological substrates of the acoustic stimulus parameters that have been extracted by the central auditory system. Those substrates set the limits for the precision of auditory discrimination.

5) Furthermore, as a measure of these central representations, the MMN also provides a means for studying auditory short-term memory, which is of crucial importance for correct speech processing and understanding. Consequently, the MMN opens a view to the temporal dimension of auditory function which, in contrast to vision, is to a great extent sequential in nature.

## Mismatch Negativity: The Original Description

In the 1970s, the most intensively studied "cognitive component" of the event-related potential (ERP) was the P3 (P300 or the late positive complex). It usually was, and is, characterized as being elicited by infrequent target events. This suggested that the two central factors underlying the P3 were stimulus deviation from the frequent events and the significance of this deviation.

Näätänen (1975), however, proposed that stimulus deviation per se, irrespective of its significance (or of the direction of attention), should produce a brain response that could be measured from the scalp. Evidence for this suggestion was obtained in experiments conducted in the Institute for Perception TNO, Soesterberg, The Netherlands, in the summer of 1975 (Näätänen, Gaillard, & Mäntysalo, 1978). In that study, which used dichotic stimulus presentation, the subject's task was to detect occasional deviant stimuli in the stimulus sequence presented to a designated ear while ignoring the concurrent sequence presented to the opposite ear. The irrelevant stimulus sequence included deviant stimuli that were physically equivalent to the deviant stimuli (targets) of the attended input sequence. The deviant stimuli were either tones of a slightly

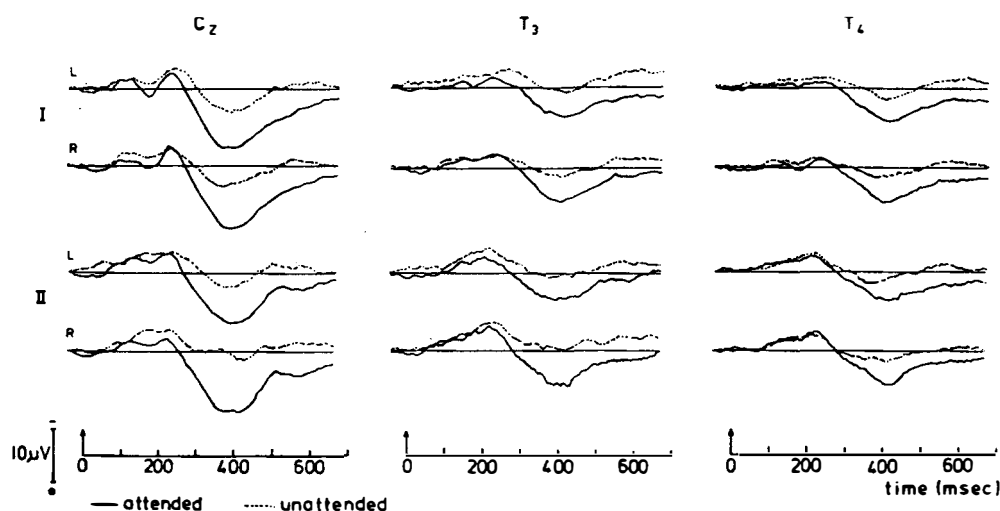


Figure 1. The difference between ERPs to deviant and standard tone pips (averaged across 9 subjects) for the three electrode positions separately for the left (L) and right (R) ear when attended and when unattended. These difference curves were obtained by subtracting the corresponding time points of the ERP to standards from the ERP to deviants. I refers to Experiment 1 in which deviants were of higher frequency than standards, II to Experiment 2 where deviants were of higher intensity than standards. (From Näätänen et al., *Acta Psychologica*, 1978; reproduced with permission).

higher frequency or tones of a slightly greater intensity than the standard tones.

It was found that the deviant stimuli both in the attended and unattended stimulus sequence elicited a negativity at the 100 to 200 msec latency range, which could not be seen in response to the standard stimuli (Fig. 1). This negativity, best visible in the deviant-minus-standard difference wave, was very similar for the attended and ignored input sequences, suggesting that attention was not required. Näätänen et al. (1978) proposed that "it may well be that a physiological mismatch process caused by a sensory input deviating from the memory trace ('template') formed by a frequent 'background' stimulus is such an automatic basic process that it takes place irrespective of the intentions of the experimenter and the subject, perhaps even unmodified by the latter. This view is supported by the fact that the mismatch negativity was similarly observed for both the attended and the unattended sides. Hence, we may here be dealing with a deviation effect rather than relevance effect, whereas the much larger P300 in the EPs to the attended signals than to the unattended signals certainly represents a relevance effect" (pp. 324–325).

On the basis of the relatively large MMN amplitudes above the temporal areas, the authors further suggested that "the mismatch negativity reflects specific auditory stimulus discrimination processes taking place in the auditory primary and association areas . . . The latter processes are suggested to be largely automatic, beyond the control of will, instructions, etc., . . ." (pp. 326–328).

### Components of the MMN

On the basis of those results, Näätänen and Michie (1979) proposed two intracranial generators for the MMN, one in auditory cortex and the other in frontal areas. The authors further suggested that the sensory-specific cortex preperceptually detects stimulus change, whereas the subsequent frontal activation might be associated with attention switch (orienting response) to stimulus change.

These proposed MMN generator loci have received support in subsequent research. In one of these studies, Alho, Paavilainen, Reinikainen, Sams, and Näätänen (1986), using the nose as the reference, found that the MMN reversed its polarity at the mastoids (below the Sylvian fissure), which suggested bilateral dipolar sources in auditory cortices along the supratemporal plane.

More direct evidence for the involvement of the auditory cortex in MMN generation was provided by the first magnetoencephalographic (MEG) recordings of the MMN (Hari et al., 1984; Sams et al., 1985a), which located the equivalent current dipole of the MMNm (the magnetic equivalent of the electric MMN) in, or in the vicinity of, the primary auditory cortex. Later MEG studies (for a review, see Alho, 1995; see also Csépe, 1995) have confirmed this observation and provided evidence for the separability of the MMNm and N1m (the magnetic equivalent of the supratemporal N1) generator loci. If the N1 (N1m) is considered to be a reflection of afferent mechanisms, then the separability of the MMNm from the N1m is consistent with the memory hypothesis rather than an afferent-mechanisms

hypothesis for MMN generation (for a review, see Ritter, Deacon, Gomes, Javitt, & Vaughan, 1995).

Recent electric (Aaltonen, Tuomainen, Laine, & Niemi, 1993; Levänen, Ahonen, Hari, McEvoy, & Sams, in press; Paavilainen, Alho, Reinikainen, Sams, & Näätänen, 1991; Scherg, Vajsar, & Picton, 1989; Giard et al., in press; Schröger, in press) and magnetic (Levänen, Hari, McEvoy, & Sams, 1993, in press) studies also have provided evidence for different or partially different generator mechanisms for MMNs to deviations in different auditory attributes and for multiple MMN generators in auditory cortex (Paavilainen et al., 1991; Lavikainen and Näätänen, 1995; for corroborating cat data, see Csépe, Karmos, & Molnár, 1987).

Evidence for frontal-cortex involvement in MMN generation followed the original suggestion of Näätänen and Michie (1979). In 1990, Giard, Perrin, Pernier, & Bouchet (1990), applying current source density analysis to MMN difference-wave topographic maps, reported evidence for both auditory-cortex and predominantly right-hemispheric frontal involvement in MMN generation. They interpreted the frontal activation in terms of an involuntary attention switch to the eliciting acoustic change, as did Näätänen and Michie (1979). The auditory-cortex component was bilateral but larger contralateral to the stimulated ear.

To summarize, the MMN has 1) a bilateral auditory-cortex generator and 2) a frontal-cortex generator. In addition, deviant stimuli seem to activate also 3) some further auditory-cortex source(s) and perhaps also 4) some subcortical sources (see Csépe, Karmos, & Molnár, 1989; Mäkelä, Salmelin, Kotila, & Hari, 1994; Kraus et al., 1994, 1995b; Kraus, McGee, Littman, Nicol, & King, 1994). For a detailed review of the cerebral sources of the MMN, see Alho (1995).

### The MMN as a Measure of Central Auditory Stimulus Representations and Their Plasticity

The MMN, in essence, indicates attention-independent, preperceptual change detection. Thus, by using the MMN, one can study what is processed as the same as, and what as different from, the previous stimuli by the auditory system. Importantly, the MMN is elicited even by small stimulus changes that approximate perceptual discrimination thresholds (the just detectable difference; Kraus et al., 1993; Sams, Paavilainen, Alho, & Näätänen, 1985b; Tiitinen, May, Reinikainen, & Näätänen, 1994; for reviews, see Näätänen & Gaillard, 1983; Näätänen & Alho, in press-a) (Fig. 2).

The fact that the MMN is a change detector for

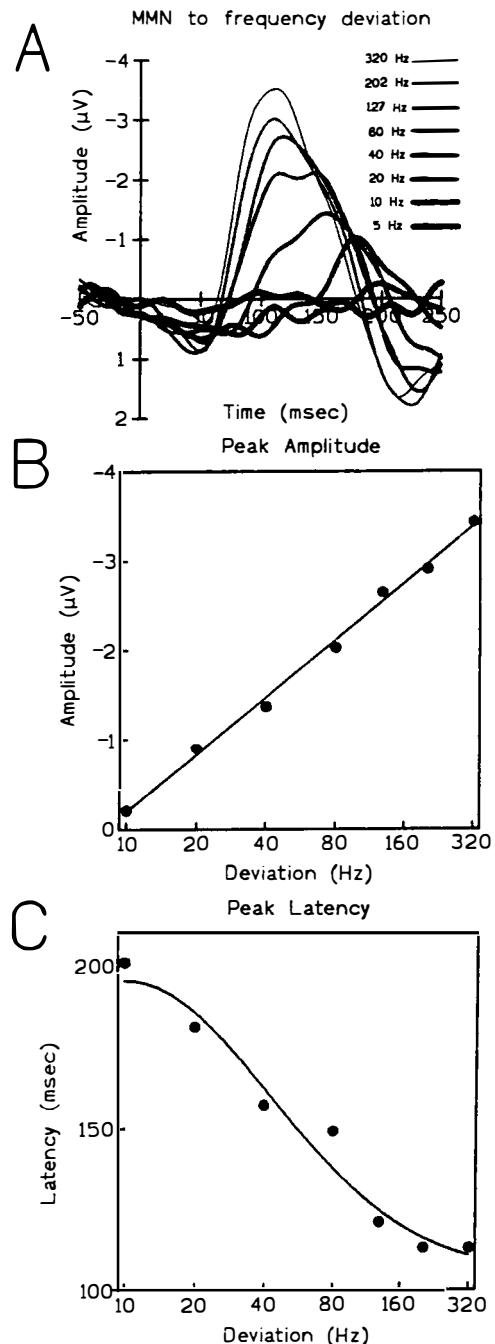


Figure 2. A) Difference waves (grand-average data from 10 subjects) obtained by subtracting ERPs to 1000-Hz standard tones from ERPs to deviant tones with higher frequencies as indicated. Each deviant occurred in separate stimulus blocks at a probability of 0.05. Note that the mismatch-negativity (MMN) amplitude is enhanced and latency shortened with increasing frequency deviation. Stimulus onset at 0 msec. B) The mean MMN peak amplitude and (C) latency as a function of the magnitude of frequency deviation. (Unpublished data from Tiitinen et al., 1994).

sequentially presented sounds implicates accurate neural representations of the preceding stimuli. Therefore, the MMN may serve as an index of these

neural stimulus representations. Näätänen and Alho (in press-a) proposed that the MMN provides the best available physiological measure of automatic central processing in audition.

According to Näätänen (1985, 1990, 1992) and Winkler, Reinikainen, and Näätänen (1993), the MMN reflects auditory sensory memory, also called "echoic memory." Several similarities between the neural trace postulated to underlie MMN generation and echoic memory are apparent. Both are attention independent (Näätänen, 1991; see, however, Woldorff, Hackley, & Hillyard, 1991) and show similar durations ranging from about 5 sec to 20 sec (for a review of behavioral literature, see Cowan, 1984; for ERP evidence, see Böttcher-Gandor & Ullsperger, 1992; Cowan, Winkler, Teder, & Näätänen, 1993; Näätänen, Paavilainen, Alho, Reinikainen, & Sams, 1987; Mäntysalo & Näätänen, 1987; for corroborating MEG evidence, see Sams, Hari, Rif, & Knuutila, 1993).

However, as pointed out by Ritter et al. (this volume; see also Cowan et al., 1993; Näätänen, 1992), single stimuli are represented in echoic memory, whereas the MMN requires two or three preceding standards before it can be elicited (at an amplitude large enough to make the presence of the MMN detectable from noise). This possible inconsistency may be explained by Cowan et al. (1993) results which suggest that a sensory-memory trace can be either in an inactive or active state with regard to possible MMN elicitation. Their data suggest that the MMN is elicited by a deviant stimulus only when a previously formed trace is first activated by a stimulus identical to the one represented by the trace.

Interestingly, these "dormant" traces implicate the existence of a much longer-lasting form of auditory sensory memory than echoic memory. These long-term traces were demonstrated by the cumulative training effects in a study in which subjects tried to detect a slight change in a complex spectro-temporal sound pattern in the course of a long experimental session (Näätänen, Schröger, Karakas, Tervaniemi, & Paavilainen, 1993c). In a number of subjects, no MMN was initially elicited by this change. Later in the session, however, the MMN began to appear (Fig. 3) and, in parallel with the MMN emergence, the subject began to hear the difference. (The discrimination training was given in three portions (early, middle, or late in the session), each of which was followed by MMN recording in passive conditions). Kraus, McGee, Carrell, King, and Tremblay (1995a, 1995b) describe a similar long-term learning effect in discriminating consonant-vowel (CV) syllables after behavioral discrimination training.

## PHASE:

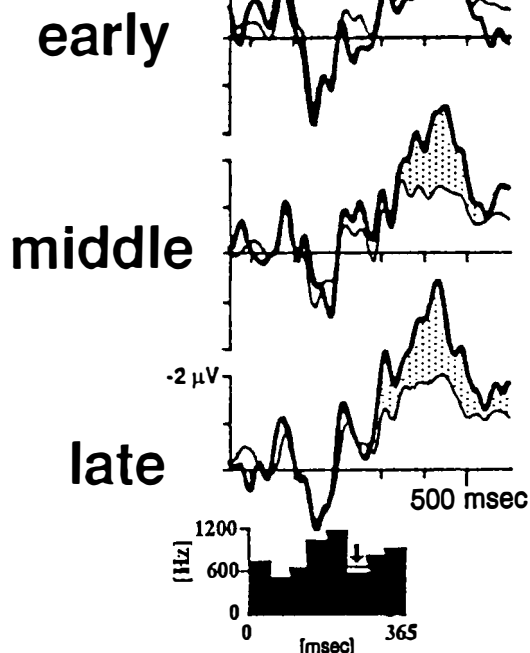


Figure 3. Grand-average ERPs at Cz to standard sound patterns (thin lines;  $p = 0.9$ ) and to deviant sound patterns (thick lines;  $p = 0.1$ ). The standard and deviant sound patterns, illustrated at the bottom, consisted of eight sinusoidal segments of different frequencies, their only difference being that, in the deviant patterns, the frequency of the sixth segment (indicated by the arrow) was higher than in the standard patterns. ERPs were recorded during the early, middle, and late phases of a session. In each phase, 1200 sound patterns were presented to subjects concentrating on a reading task. The behavioral discrimination performance of the subjects belonging to "improvers" considerably improved in a sound-pattern discrimination test administered after each phase. This improvement was paralleled by MMN emergence (middle blocks) and enhancement (late blocks). (Adapted from Näätänen et al., *NeuroReport*, 1993c).

Importantly, these long-term neural traces could serve as recognition patterns in the analysis of the auditory environment (see Näätänen, 1992; Näätänen and Alho, in press-b). For an organism to recognize a complex sound as the same as some previously heard sound, a sensory representation of that previous sound must be activated by the current input. The development of a network of such neural traces for initially difficult or new sounds (from phonemes to words and short sentences) is likely to be essential in learning to hear correctly the acoustic properties of a foreign language. The development of those neural traces, or recognition patterns, would be a prequalification for successful semantic analysis and understanding of a new language (see Näätänen, 1992).

Such traces apparently can be developed only when subjects attend to auditory stimuli (discrimination training). Passive long-duration exposure *per se* is not sufficient (Näätänen et al., 1993c). Thus, effort seems to be essential for the development of these recognition patterns. After such a trace has developed, however, it appears to function automatically in service of auditory analysis, judging from the fact that the MMN could be recorded in passive conditions following discrimination training (Näätänen et al., 1993c; see also Kraus et al., 1995b).

These MMN findings clarify one of the central issues of the nature of sensory memory, namely, whether this memory is a precategorical, raw (hard-wired) replica of acoustic stimulation (Crowder & Morton, 1969; Kallman & Massaro, 1979; Neisser, 1967), or whether there are adaptive changes in this system (see Port, 1988). The MMN data reviewed above clearly indicate plastic changes in the neurophysiological basis of sensory memory such that long-duration, probably permanent, traces are formed for new complex stimuli when they start to occur relatively frequently, e.g., when we have moved to a foreign-language environment. This new stimulation gradually forms a large set of new traces corresponding to phonemes, syllables, perhaps even words and short sentences, which then serve as recognition patterns in our acoustic analysis of the sounds of a new language.

### **The MMN and Accuracy in Behavioral Discrimination of Acoustic Change**

In the preceding section, it was mentioned that the sensitivity of the MMN to slight stimulus changes approximates that of behaviorally detecting these changes (and probably even exceeds the behavioral sensitivity; see Näätänen and Alho, *in press-a*). If this correspondence holds true, then the MMN may hold potential as an objective measure of normal and pathological sensory discrimination in audition. Fortunately, recent studies have provided such evidence. For example, Lang et al. (1990) showed that there is a strong relationship between the MMN amplitude recorded in passive conditions and individual behavioral pitch-discrimination ability (see Lang et al., 1995). In addition, evidence for the relationship between the behavioral discrimination ability and the presence/absence of the MMN is provided by Kraus' studies with CV syllables presented to cochlear-implant patients (see Kraus et al., 1993; for a review, see Kraus et al., 1995b).

Converging intraindividual evidence for a relation between behavioral discrimination threshold and MMN amplitude can be found from the back-

ward-masking studies of Winkler and Näätänen (1992) and Winkler et al. (1993). These authors demonstrated a similar time course for recovery of recognition memory and MMN amplitude when the time interval between the stimuli of the MMN paradigm and the following masking stimulus was gradually prolonged. When the masking stimulus followed each standard and deviant of the MMN paradigm within a short interval, such as 20 or 50 msec, no MMN was elicited by deviants nor was the subject able to tell standards and deviants apart. However, when this interval was prolonged to 150 msec, both measures showed considerable recovery.

Further converging intraindividual evidence for the correlation between behavioral discrimination ability and MMN amplitude is provided by the aforementioned parallel emergence of the MMN to slight changes in a complex spectro-temporal pattern and the subject's behavioral ability to discriminate these changes as a function of discrimination training during an experimental session (Näätänen et al., 1993c; see also Kraus et al., 1995b).

Thus, one may conclude that the MMN may provide an objective feature- and stimulus-specific measure of auditory discrimination ability. This measure could be used in normal persons to study individual perceptual capabilities such as components of musical talent (e.g., pitch, interval, duration, rhythm perception) and training effects in these capabilities. In auditory pathology, the MMN could be used for diagnostic and prognostic purposes. For example, the MMN might be used to determine whether aphasia (Aaltonen et al., 1993) or dysphasia (Kraus & McGee, 1994; Korpilahti & Lang, 1994) results from auditory-system inability to develop different representations for different phonemes and syllables, or from a higher-level dysfunction. Possible applications of the MMN will be discussed in the end of this article and in considerably more detail by Kraus et al. (1995b); Kurtzberg, Vaughan, Kreuzer, and Fliegler (1995); Ponton and Don (1995); and Lang et al. (1995).

### **The MMN and Attention**

The use of the MMN as an objective measure of auditory function is to a large extent based on the assumed full or partial independence of the MMN from attention. If the MMN were elicited only in the presence of attention, then it could not be regarded as being free from attention-related variations that affect behavioral measures of auditory function. Moreover, it would not be possible to associate the MMN with attention switch to change in an initially unattended sound (see Näätänen, 1985).

Several studies have shown that the MMN elic-

ited by deviant stimuli when they are targets of the attended sound sequence or when the sounds are ignored are of very similar amplitude (e.g., Näätänen, Simpson, & Loveless, 1982). Deviants in the attended stimulus sequence usually elicit a larger negativity (revealed by the difference wave) than when the auditory stimuli are ignored, but this difference is due to the superimposition of the N2b component on the MMN (Näätänen et al., 1982; Näätänen, Sams, & Alho, 1986; Näätänen, Sams, Järvillehto, & Soininen, 1983). Comparisons of the MMNm between active and passive conditions have yielded very similar amplitudes (Kaukoranta, Sams, Hari, Hämäläinen, & Näätänen, 1989; Lounasmaa, Hari, Joutsiniemi, & Hämäläinen, 1989). Consistently with this, the MEG does not register the N2b generator process (probably due to the radial orientation of the generator).

In contrast to results suggesting attentional independence of the MMN amplitude, the MMNm recorded by Aulanko, Hari, Lounasmaa, Sams, and Näätänen (1993) for a phonetic change (/ba/-/da/, or vice versa) was larger in amplitude when phonetic stimuli were attended than when they were ignored. However, their subsequent study failed to replicate this effect (Aulanko, Ilmoniemi, & Sams, 1995). For MMNs to phonetic changes, see Maiste, Wiens, Hunt, Scherg, and Picton (1995).

Attention is more strongly focused during concurrent presentation of the to-be-attended and -ignored stimulus streams, most typically when they are presented dichotically with a rapid rate (Hillyard et al., 1973; for reviews, see Hillyard, Mangun, Woldorff, & Luck, in press; Näätänen, 1982, 1990, 1992). Under such conditions, the amplitude of the frequency-change MMN still seems to be unaffected by the direction of attention (Näätänen, Paavilainen, Tiitinen, Jiang, & Alho, 1993b; Paavilainen, Tiitinen, Alho, & Näätänen, 1993; however, see Alho, Woods, Algazi, & Näätänen, 1992; Trejo, Ryan-Jones, & Kramer, in press). In contrast, the MMN for intensity reduction is strongly attenuated, though not fully eliminated, in the absence of attention (Woldorff et al., 1991; Näätänen et al., 1993b; for comparable MEG data, see Woldorff et al., 1993).

Nevertheless, no data have demonstrated a total disappearance of the MMN in the absence of attention. Näätänen (1991), therefore, suggested that the sensory analysis resulting in neural sound representations is not affected, but that the excitability of the MMN process triggered by a deviant stimulus might be dampened in the absence of attention. He proposed a division of neurons involved in the MMN process into 1) computational and 2) amplifying ones, suggesting that it is the latter neurons that might be modulated by attention.

In summary, it appears that the MMN to frequency change is strongly attention independent in most conditions. However, in the most intensely focused conditions, the MMN to intensity change is attenuated but not fully abolished. In general, the degree of attention independence of the MMN is well sufficient to justify its use as an objective measure of sensory analysis in audition as well as its interpretation in terms of a cerebral mechanism of attention switch to a change in an unattended sound sequence.

These views have recently received strong support from the dramatic results of Kane, Curry, Butler, and Cummins (1993), which demonstrated the emergence of a well-defined MMN in coma patients 1 to 2 days before they regained their consciousness, and a continuous absence of the MMN in those patients who later died. In addition, some human sleep data (Campbell, Bell, & Bastien, 1991; Sallinen, Kaartinen, Ruusuvirta, & Lyytinen, in press; for a review, see Näätänen and Lyytinen, in press) and intracranial recordings from anesthetized cats (Csépe et al., 1989) and guinea pigs (Kraus et al., 1994a, 1994b) provide evidence for the occurrence of the MMN even during sleep or anesthesia. However, not all studies have found an MMN in sleep (Paavilainen et al., 1987).

### **The Role of the MMN Process in Conscious Perception of Stimulus Change**

Näätänen and Michie (1979; see also Näätänen, 1990, 1992) proposed that the functional significance of the MMN generator is to initiate attention switch (orienting response) to the eliciting stimulus change, suggesting further that the frontal component might be implicated in this function. The correspondence of the MMN mechanism to Sokolov's (1975) orienting-response theory is remarkable. The memory traces involved in MMN generation resemble Sokolov's neuronal models and the MMN process corresponds to his neuronal-mismatch process, with a few exceptions (see Näätänen, 1986). The MMN-generator activation, however, may not necessarily lead to a (full) orienting response but, according to Näätänen (1986), could result in a brief covert attention switch that may be the central element of the orienting response. Consistent with this hypothesis, Lyytinen, Blomberg, and Näätänen (1992) showed that an MMN can be elicited without skin-conductance response and heart-rate decrease indicators of the orienting response.

The hypothesis in which the MMN generator plays a role as an involuntary attention trigger is strongly supported by the very recent results of Schröger (1994b). In a selective dichotic-listening

experiment, he found that the reaction time to an infrequent softer-intensity stimulus in the right ear increased and the hit rate attenuated when this target stimulus was preceded (with a 200-msec lead time) by a frequency deviant in the left ear. In addition, when the frequency deviation was 50 Hz (standard 700 Hz), the RT increased by 12 msec, when the deviation was 200 Hz, the RT prolongation grew to 26 msec. Both frequency deviants elicited MMNs while the wider frequency deviant also elicited N2b-P3a waves. According to Schröger (1994b), "this performance decrement was probably due to attentional capture to the to-be-ignored channel triggered by the deviants of this channel." He further proposed that the data pattern obtained supports the hypothesis that the neural processes generating the MMN may be involved in a mechanism of passive attention switch" (pp. 88–89).

Further evidence for the MMN being associated with involuntary attention switch is provided by the fact that the MMN is often followed by a relatively sharp, central positivity P3a (see Squires, Squires, & Hillyard, 1975), which might indicate the occurrence of a brief attention switch (see Sams et al., 1985b; Lyytinen et al., 1992). Other more-or-less regular physiological concomitants of the MMN might be a phase advance of the steady-state response elicited by a continuous background stimulation around 40 Hz (Makeig, 1995) and some late, slow frontal activity (Näätänen et al., 1982, 1983; Alho, Woods, Algazi, Knight, & Näätänen, 1994).

For a model suggesting the role of the MMN generator activation in attention switch, see Näätänen (1990, 1992).

### **The Traces of Sensory Memory and the Emergence of Perception**

When a sound is presented, the stimulus features first are rapidly mapped by subcortical and cortical afferent mechanisms. The emergence of this stimulus-determined activation pattern is, according to Näätänen (1992), followed by trace formation, the mapping of this stimulus-specific afferent pattern into the neural systems of sensory memory. This rapid emergence of the memory trace might underlie stimulus perception (Näätänen, 1992). It is presumably in this trace-formation process where outcomes from the distributed set of different feature-specific afferent systems are integrated. Näätänen (1992) further proposed a sliding "temporal window of integration," an approximately 200-msec period of the most recent past in which all acoustic events falling within this period are integrated in perception. This temporal window of integration might be

of critical importance for central auditory function such as speech processing, as will be explained later.

This 200-msec duration of the temporal window of integration is supported by, among other things, the continuation of loudness summation when stimulus duration is gradually increased up to 200 msec from stimulus onset (Scharf & Houtsma, 1986), and by the occurrence of backward-masking effects when the masker is presented within a similarly short interval from stimulus onset (see Foyle & Watson, 1984; Hawkins & Presson, 1986; Massaro, Cohen, & Idson, 1976; Winkler et al., 1993). In addition, although the N1 amplitude to the second stimulus is continuously attenuated when the ISI between two paired stimuli is shortened (for a review, see Näätänen & Picton, 1987), this attenuation is dramatically reversed when the second stimulus falls within the proposed temporal window of integration of the first stimulus (Loveless et al., 1989; Budd and Michie, *in press*).

Additional evidence was provided by Tervaniemi, Saarinen, Paavilainen, Danilova, and Näätänen (1994b), who found that the omission of the second tone of a tone pair elicits an MMN only when the within-pair ISI is very short. (The subject was reading a book while the stimuli were presented.) The omission MMN was obtained with an ISI of 200 msec from stimulus onset. The MMN disappeared when the ISI was 300 msec. Interestingly, a kind of anticipatory negativity, "integration negativity," preceded the second tone with the shortest ISI, thereby suggesting that those two closely paced tones formed a single sensory event. Furthermore, Yabe, Tervaniemi, Reinikainen, and Näätänen (1995) recently found an MMN to stimulus omission in subjects reading a book when the onset-to-onset ISI in the stimulus block was 100 msec or when it was 125 msec. They observed no MMN when the ISI was 150 msec or longer.

The temporal window of integration also might be of central importance to musical experience and to speech perception. Näätänen (1990) proposed that the continuously sliding temporal window of integration actually corresponds to the psychological presence, thereby providing perception with a kind of sliding background or reference of the immediate past of about 200 msec. According to him, "this sensory persistence might considerably expand the window of the 'psychological presence' in audition relative to the timeless 'cutting edge' of physical presence that continuously turns the future into the past" (Näätänen, 1990, p. 275). This temporal window of integration is essential for the subjective smooth continuity in much of our auditory perception.

Thus, a view is advanced according to which the memory-trace formation is a fast, automatic sensory

event that ends about 200 msec from stimulus onset. It underlies (providing the specific informational contents for) the transient perception (hearing) of the sound. In this memory-trace formation process, both parallel (output from different afferent systems) and sequential temporal integration of sensory information occur. It is important to realize that temporal integration does not mean "condensing" the time dimension or any loss of temporal information, but rather an interaction of closely paced events at the perceptual level (e.g., an integration of two closely paced tones as a single perceptual event; Tervaniemi et al., 1994b). This integration usually is of "constructive" nature, structuring the auditory perceptual world in a way similar to the operation of Gestalt laws in visual perception (Fieandt & Moustgaard, 1977; Goldstein, 1989; see also Bregman, 1990). However, it can sometimes be destructive. For example, if one of the stimuli falling on the window of integration is much stronger in intensity than the other(s), then the original elements cannot be maintained in perception, and backward or forward masking occurs.

What is clear is that the traces of the memory system involved in MMN generation do not represent static stimuli and their sensory attributes, but rather these stimuli as events occurring in time, that is, stimuli in their temporal frame of reference. Thus, the time dimension is a critical aspect of these traces. Consistent with this motion, the MMN can be obtained with different kinds of merely temporal stimulus changes such as changes in stimulus duration (Näätänen, Paavilainen, & Reinikainen, 1989; for corresponding MEG data, see Kaukoranta et al., 1989), stimulus order (Nordby, Roth, & Pfefferbaum, 1988a; Tervaniemi et al., 1994b), the order of segments in a spectrotemporal stimulus pattern (Schröger, Näätänen, & Paavilainen, 1992; Schröger, 1994a), ISI duration (shortening) (Ford & Hillyard, 1981; Näätänen, Jiang, Lavikainen, Reinikainen, & Paavilainen, 1993a; Nordby et al., 1988b), the direction of a frequency glide (Pardo & Sams, 1993; Sams & Näätänen, 1991), or in a rhythmic stimulus pattern formed by several tones (Imada et al., 1993).

This view of trace emergence implicates that the trace strength (see Winkler, 1993) should be at its maximum at 200 msec from stimulus onset when the trace formation ends, and thereafter should gradually decay. Consequently, the largest MMN should be obtained with ISIs of 200 msec or less (when the interval between deviant stimuli does not become too short). Corroborating evidence was provided by Näätänen et al. (1987), whose deviant stimuli occurred on an average once per 6 sec, whereas the temporal density of the standards was varied. Considerably larger MMNs were obtained

when the (onset-to-onset) ISI was 50 or 100 msec than when it was 300 msec or longer.

### The MMN as an Expression of Primitive Sensory Intelligence

In the preceding section, a neural-trace formation view was proposed in which integrative processes occur, with the consequence that the auditory representation of physical reality becomes structured, shaped, and segregated in a more easily and rapidly manageable form for subsequent interpretative processes. This proposal was an analogy to the operation of Gestalt laws in visual perception. Such "shaping" processes might be necessary for our ability to extract essential auditory information from the total, continuously changing auditory excitation pattern, thereby forming a basis for higher cognitive processes.

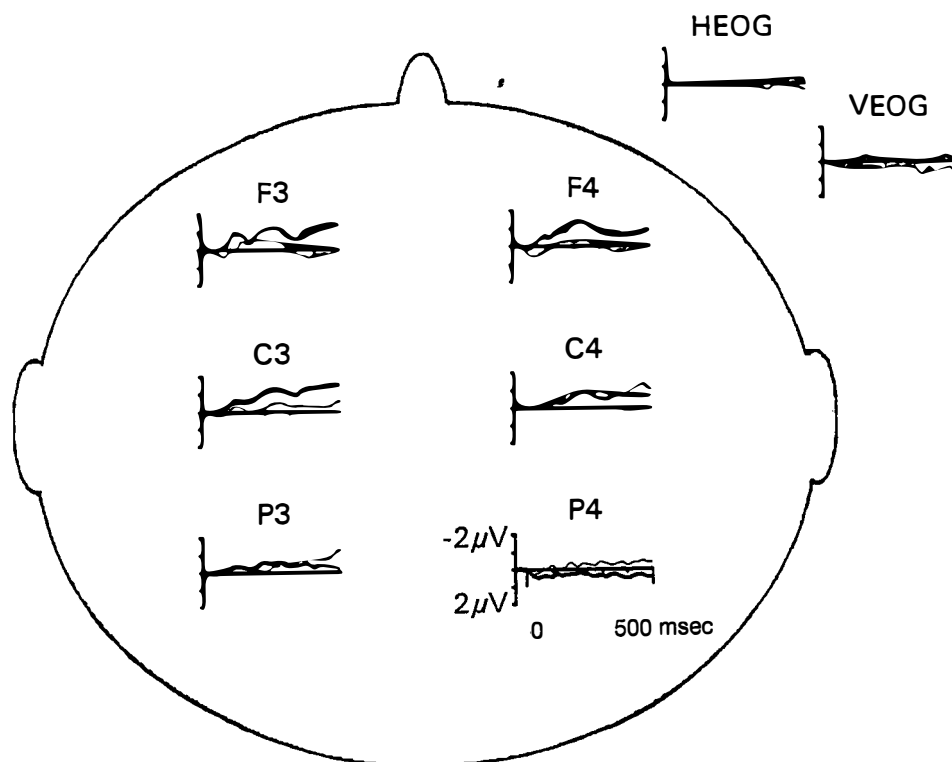
Interestingly, some recent results suggest the participation of processes that could be characterized as expressions of primitive sensory intelligence in this memory-trace formation. In one of their experimental conditions, Saarinen, Paavilainen, Schröger, Tervaniemi, and Näätänen (1992) used ascending stimulus pairs as standard stimuli, the second member of the tone pair being slightly higher in frequency than the first member. The stimulus pair could occur at several different frequency levels. Thus, the only constant feature of the standards was the direction of the within-pair frequency change. The deviants were tone pairs with frequency change in the opposite direction. The subject was reading a book during the session.

The MMN elicited by these deviants was interpreted by the authors as a sign of primitive, automatic-level sensory intelligence, with the standards in this case representing the concept of an ascending pair (with no specific frequency values) and the deviants the concept of a descending pair. Thus, the memory trace appeared to have incorporated a rule or generalization extracted from the stream of physically varying standards. The magnetic results of Pardo and Sams (1993) who used rising and falling frequency glides starting from varying frequency levels, might be interpreted in a similar way.

Näätänen (1992) proposed that the functional significance of the trace formation process is perhaps not only to represent the present and immediate past, that is, to act as a memory, but also to provide a continuously updated sensory prediction of the immediate future. Hence, this trace-formation process might, in fact, express automatic sensory extrapolatory activity, thereby providing a sensory prediction of the immediate future which then could

Difference waves ——— deviant /i/ - standard /y/  
 ——— deviant /y/i/ - standard /y/

Figure 4. Difference waves (grand-average data from 12 newborns) obtained by subtracting ERPs to the standard Finnish /y/ from those to the deviant /i/ (thick line). Thin lines present the corresponding difference waves when the deviant stimulus was a boundary between /y/ and /i/. The newborns were in slow-wave sleep during recordings. (From Cheour-Luhtanen et al., *Hearing Research*, in press; reproduced with permission).



serve as a reference for stimulus-triggered sensory processes of that immediate future.

This suggestion was tested by Tervaniemi, Maury, and Näätänen (1994a). Their standards were a continuously ascending sequence of tones with equal steps. Their deviants were occasional descending tones (to the preceding frequency). The MMN was elicited by these deviants, which was interpreted by the authors as evidence for automatic sensory extrapolatory activity because the MMN was elicited by a deviation from no actually presented stimulus but rather from one automatically predicted on the basis of the regular stepwise frequency increments in the preceding sequence of standard stimuli.

### The MMN: Perspectives of Application

Despite its rather recent discovery, the MMN already holds a number of promising applications. These applications might be divided into four main categories. The MMN might be an indicator of 1) the functional state of the cortex, 2) sensory and perceptual capabilities, 3) pathology of automatic processing, or 4) neural plasticity.

First, as an index of the functional state of the cortex, the general rule seems to be that the MMN amplitude is larger for better functional states. For example, the MMN is larger in states of higher vigilance (see Lang et al., 1995). Furthermore, drugs lowering the performance level in demanding cognitive and motor tasks such as sedative drugs (see Born, Fehm-Wolfsdorf, Lutzenberger, Voigt, & Fehm, 1986; Born, Kern, Fehm-Wolfsdorf, & Fehm, 1987; Duncan & Kaye, 1987; Pietrowsky, Fehm, & Born, 1990) and alcohol (Jääskeläinen et al., in press-a, in press-b) also attenuate the MMN amplitude. One promising application of the MMN along these lines might be to use it in the prognosis of the state of comatose patients, as was suggested by the Kane et al. (1993) study.

Second, the use of the MMN as an objective measure of sensory/perceptual capabilities both in normal subjects and in auditory pathology was mentioned above (for detailed accounts, see Kraus et al. 1995b; Kurtzberg et al., 1995; Lang et al., 1995; Ponton and Don, 1995). For example, in normal children, the MMN might be used for objective evaluation of some sensory/perceptual components

of musical talents. Such information would be useful for parents who are considering enrolling their child in an ambitious musical training program. In auditory pathology, the MMN might be used for objective evaluation of cochlear-implant function (Kraus et al., 1995b; Ponton and Don, 1995) and for the objective diagnosis of aphasic patients (Aaltonen et al., 1993; Csépe, 1995), dysphasic children (Korpilahti and Lang, 1994; Lang et al., 1995), and of children with auditory-based learning disabilities (Kraus & McGee, 1994; Kraus et al., 1995b).

The MMN also might be helpful in the early identification of newborn and prespeech infants with central hearing disorders. To this end, Alho, Sainio, Sajaniemi, Reinikainen, and Näätänen (1990) recorded newborn infants' MMNs to frequency changes. Cheour-Luhtanen et al. (in press) have measured infant MMNs to phoneme changes to explore the possibility of using the presence/absence of these MMNs in evaluating cortical-level auditory function for early detection of hearing disorders (see Fig. 4). Early detection is important because behavioral test results often are obtained too late to prevent a delay in speech development (for the use of ERPs in the diagnosis of auditory dysfunction in infants and small children, see Kurtzberg, 1989; Kurtzberg, Stapells, & Wallace, 1988; Kurtzberg et al., 1995).

Third, the MMN might serve as an index of central deficits in auditory processing that accompany some severe psychopathology. For example, several studies have shown attenuated MMN amplitudes in patients with schizophrenia (Oades, 1991; Shelley, Ward, Catts, Michie, Andrews, & McConaghy, 1991; Schrott, Cohen, Bergman, & Hopmann, 1992; Catts et al., in press; Javitt, Doneshka, Zylberman, Ritter, and Vaughan, 1993), which can be found both in patients with and without medication (Catts et al., in press). MMN attenuation also has been found in patients with Alzheimer's disease (Pekkonen, Jousmäki, Reinikainen, & Partanen, in press-b) and in those with Parkinson's disease (Pekkonen, Jousmäki, Könönen Reinikainen, & Partanen, in press-a).

Fourth, the MMN might be useful as an index of neural plasticity in the auditory system (Kraus et al., 1995b; Näätänen et al., 1993c). Pekkonen, Jousmäki, Partanen, and Karhu (1993; Pekkonen et al., 1995) showed that the MMN is of a very similar amplitude in old and young subjects when short ISIs are used. However, with longer ISIs, the MMN amplitude was considerably more attenuated in old compared with young subjects, which might imply decreased neural plasticity with aging (see, however, Czigler, Csibra, & Csontos, 1992). A very similar pattern of results also was obtained in patients with Alzheimer's disease (Pekkonen et al., in

press-b) and in those with Parkinson's disease (Pekkonen et al., in press-a).

Address for correspondence: Dr. Risto Näätänen, Cognitive Psychophysiology Research Unit, Department of Psychology, University of Helsinki, Helsinki, Finland

## REFERENCES

- Aaltonen, O., Tuomainen, J., Laine, M., & Niemi P. (1993). Discrimination of speech and non-speech sounds by brain-damaged subjects: Electrophysiological evidence for distinct sensory processes. *Brain and Language*, 44, 139–152.
- Alho, K. (1995). Cerebral generators of mismatch negativity (MMN) and its magnetic counterpart (MMNm) elicited by sound changes. *Ear and Hearing*, 16, 38–50.
- Alho, K., Paavilainen, P., Reinikainen, K., Sams, M., & Näätänen, R. (1986). Separability of different negative components associated with auditory stimulus processing. *Psychophysiology*, 23, 613–624.
- Alho, K., Sainio, K., Sajaniemi, N., Reinikainen, K., & Näätänen, R. (1990). Event-related brain potential of human newborns to pitch change of an acoustic stimulus. *Electroencephalography and Clinical Neurophysiology*, 77, 151–155.
- Alho, K., Woods, D. L., Algazi, A., Knight, R. T., & Näätänen, R. (in press). Lesions of frontal cortex diminish the auditory mismatch negativity. *Electroencephalography and Clinical Neurophysiology*.
- Alho, K., Woods, D. L., Algazi, A., & Näätänen, R. (1992). Intermodal selective attention. II: Effects of attentional load on processing auditory and visual stimuli in central space. *Electroencephalography and Clinical Neurophysiology*, 82, 356–368.
- Aulanko, R., Hari, R., Lounasmaa, O. V., Näätänen, R., & Sams, M. (1993). Phonetic invariance in the human auditory cortex. *NeuroReport*, 4, 1356–1358.
- Aulanko, R., Ilmoniemi, R. J., & Sams, M. (1995). *Detection of phonetic changes in natural speech*. Manuscript submitted for publication.
- Born, J., Fehm-Wolfsdorf, G., Lutzenberger, W., Voigt, K. H., & Fehm, H. L. (1986). Vasopressin and electrophysiological signs of attention in man. *Peptides*, 7, 189–193.
- Born, J., Kern, W., Fehm-Wolfsdorf, G., & Fehm, H. L. (1987). Cortisol effects on attentional processes in man as indicated by event-related potentials. *Psychophysiology*, 24, 286–292.
- Böttcher-Gandor, C., & Ullsperger, P. (1992). Mismatch negativity in ERPs to auditory stimuli as a function of varying interstimulus interval. *Psychophysiology*, 29, 546–550.
- Bregman, A. S. (1990). *Auditory scene analysis: The perceptual organization of sound*. Cambridge: Bradford Books.
- Budd, B., & Michie, P. T. (in press). Facilitation of the N1 peak of the auditory ERP at short stimulus intervals. *NeuroReport*.
- Campbell, K., Bell, I., & Bastien, C. (1991). Evoked potential measures of information processing during natural sleep. In R. Broughton & R. Ogilvie (Eds.), *Sleep, arousal, and performance* (pp. 88–116). Cambridge, MA: Birkhauser.
- Catts, S. V., Shelley, A.-M., Ward, P. B., Liebert, B., McConaghy, N., Andrews, S., & Michie, P. T. (in press). Brain potential evidence for an auditory sensory memory deficit in schizophrenia. *Am J Psychiatry*.
- Cheour-Luhtanen, M., Alho, K., Kujala, T., Sainio, K., Reinikainen, K., Renlund, M., Aaltonen, O., Eerola, O., & Näätänen, R. (in press). Mismatch negativity indicates vowel discrimination in newborns. *Hearing Research*.
- Cowan, N. (1984). On short and long auditory stores. *Psychological Bulletin*, 96, 341–370.

- Cowan, N., Winkler, I., Teder, W., & Näätänen, R. (1993). Memory prerequisites of the mismatch negativity in the auditory event-related potential (ERP). *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 19, 909-921.
- Crowder, R. G., & Morton, J. (1969). Precategorical acoustic storage (PAS). *Perception and Psychophysics*, 5, 365-373.
- Csépe, V. (1995). On the origin and development of the mismatch negativity. *Ear and Hearing*, 16, 90-103.
- Csépe, V., Karmos, G., & Molnár, M. (1989). Subcortical evoked potential correlates of early information processing: Mismatch negativity in cats. In E. Basar & T. H. Bullock (Eds.), *Springer series in brain dynamics 2* (pp. 278-289). Berlin: Springer Verlag.
- Csépe, V., Karmos, G., & Molnár, M. (1987). Evoked potential correlates of stimulus deviance during wakefulness and sleep in cat: Animal model of mismatch negativity. *Electroencephalography and Clinical Neurophysiology*, 66, 571-578.
- Czigler, I., Csibra, G., & Csontos, A. (1992). Age and inter-stimulus interval effect on event-related potentials to frequent and infrequent auditory stimuli. *Biological Psychology*, 33, 195-206.
- Duncan, C. C., & Kaye, W. H. (1987). Effects of clonidine on event-related potential measures of information processing. In R. Johnson, Jr., J. W. Rohrbaugh, & R. Parasuraman (Eds.), *Current trends in event-related potential research* (pp. 527-531). Amsterdam: Elsevier.
- Fieandt, K. von, & Moustgaard, I. K. (1981). *The perceptual world*. London: Academic Press.
- Ford, J. M., & Hillyard, S. A. (1981). Event related potentials, ERPs, to interruptions of steady rhythm. *Psychophysiology*, 18, 322-330.
- Foyle, D. C., & Watson, C. S. (1984). Stimulus-based versus performance-based measurement of auditory backward recognition masking. *Perception and Psychophysics*, 36, 515-522.
- Giard, M.-H., Lavikainen, J., Reinikainen, K., Perrin, F., Bertrand, O., Thévenet, M., Pernier, J., & Näätänen, R. (in press). Separate representation of stimulus frequency, intensity, and duration in auditory sensory memory. *Journal of Cognitive Neuroscience*.
- Giard, M.-H., Perrin, F., Pernier, J., & Bouchet, P. (1990). Brain generators implicated in processing of auditory stimulus deviance: A topographic event-related potential study. *Psychophysiology*, 27, 627-640.
- Goldstein, E. B. (1989). *Sensation and perception* (3rd ed.). Belmont, CA: Wadsworth Publishing Co.
- Hari, R., Hämäläinen, M., Ilmoniemi, R., Kaukoranta, E., Reinikainen, K., Salminen, J., Alho, K., Näätänen, R., & Sams, M. (1984). Responses of the primary auditory cortex to pitch changes in a sequence of tone pips: Neuromagnetic recordings in man. *Neuroscience Letters*, 50, 127-132.
- Hawkins, H. L., & Presson, J. C. (1986). Auditory information processing. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance* (pp. 61-64). New York: Wiley.
- Hillyard, S. A., Mangun, G. R., Woldorff, M. G., & Luck, S. J. (in press). Neural systems mediating selective attention. In: M. S. Gazzaniga (Ed.), *The cognitive neurosciences*. Cambridge, MA: MIT Press.
- Imada, T., Fukuda, K., Kawakatsu, M., Mashiko, T., Okada, K., Hayashi, M., Aihara, K., & Kotani, M. (1993). Mismatch fields evoked by a rhythm passage. *Abstracts of Biomag '93 Wien* (pp. 118-119).
- Jääskeläinen, I. P., Pekkonen, E., Alho, K., Sinclair, J. D., Sillanauke, P., & Näätänen, R. (in press-a). Dose-related effect of alcohol on mismatch negativity and reaction time performance. *Alcohol*.
- Jääskeläinen, I. P., Lehtokoski, A., Alho, K., Kujala, T., Pekkonen, E., Sinclair, J. D., Näätänen, R., & Sillanauke, P. (in press-b). Low dose of ethanol suppresses mismatch negativity of auditory event-related potentials. *Alcoholism: Clinical and Experimental Research*.
- Javitt, D. C., Doneshka, P., Zylberman, I., Ritter, W., & Vaughan, H. G. Jr. (1993). Impairment of early cortical processing in schizophrenia.
- Kallman, H. J., & Massaro, D. W. (1979). Similarity effects in backward recognition masking. *Journal of Experimental Psychology: Human Perception and Performance*, 5, 110-128.
- Kane, N. M., Curry, S. H., Butler, S. R., & Cummins, B. H. (1993). Electrophysiological indicator of awakening from coma. *The Lancet*, 341, 688.
- Kaukoranta, E., Sams, M., Hari, R., Hämäläinen, M., & Näätänen, R. (1989). Reactions of human auditory cortex to a change in tone duration. *Hearing Research*, 41, 15-22.
- Korpilahti, P., & Lang, H. (1994). Auditory ERP components and mismatch negativity in dysphasic children. *Electroencephalography and Clinical Neurophysiology*, 91, 256-264.
- Kraus, N., & McGee, T. (1994). Mismatch negativity in the assessment of central auditory function. *American Journal of Audiology*, 3, 139-151.
- Kraus, N., McGee, T., Carrell, T., King, C., Littman, T., & Nicol, T. (1994a). Discrimination of speech-like contrasts in the auditory thalamus and cortex. *Journal of the Acoustical Society of America*, 96, 2758-2768.
- Kraus, N., McGee, T., Carrell, T., King, C., & Tremblay, K. (1995a). Central auditory system plasticity associated with speech discrimination learning. *Journal of Cognitive Neuroscience*, 7, 27-34.
- Kraus, N., McGee, T., Carrell, T., Sharma, A., Koch, D., King, C., Tremblay, K., & Nicol, T. (1995b). Neurophysiologic bases of speech discrimination. *Ear and Hearing*, 16, 19-37.
- Kraus, N., McGee, T., Littman, T., Nicol, T., & King, C. (1994b). Non-primary auditory thalamic representation of acoustic change. *Journal of Neurophysiology*, 72, 1270-1277.
- Kraus, N., McGee, T., Micco, A., Sharma, A., Carrell, T., & Nicol, T. (1993). Mismatch negativity in school-age children to speech stimuli that are just perceptibly different. *Electroencephalography and Clinical Neurophysiology*, 88, 123-130.
- Kurtzberg, D. (1989). Cortical event-related potential assessment of auditory system function. *Seminars in Hearing*, 10, 252-261.
- Kurtzberg, D., Stapells, D. R., & Wallace, I. F. (1988). Event-related potential assessment of auditory system integrity: Implications for language development. In P. Vietze and H. G. Vaughan, Jr. (Eds.), *Early identification of infants with developmental disabilities* (pp. 160-180). Philadelphia: Grune & Stratton.
- Kurtzberg, D., Vaughan, H. G. Jr., Kreuzer, J. A., & Fliegler, K. Z. (1995). Developmental studies and clinical application of mismatch negativity: problems and prospects. *Ear and Hearing*, 16, 104-116.
- Lang, A. H., Eerola, O., Korpilahti, P., Holopainen, I., Salo, S., Uusipaikka, E., & Aaltonen, O. (1995). Clinical applications of the mismatch negativity. *Ear and Hearing*, 16, 117-129.
- Lang, A. H., Nyrke, T., Ek, M., Aaltonen, O., Raimo, I., & Näätänen, R. (1990). Pitch discrimination performance and auditory event-related potentials. In C. H. M. Brunia, A. W. K. Gaillard, & A. Kok (Eds.), *Psychophysiological brain research, Vol. 1* (pp. 294-298). Tilburg: Tilburg University Press.
- Lavikainen, J., & Näätänen, R. (1995). *Evidence for a temporal mismatch negativity component*. Manuscript submitted for publication.
- Levänen, S., Ahonen, A., Hari, R., McEvoy, L., & Sams, M. (in press). Deviant auditory stimuli activate human left and right auditory cortex differently. *Cerebral Cortex*.

- Levänen, S., Hari, R., McEvoy, L., & Sams, M. (1993). Responses of the human auditory cortex to changes in one versus two stimulus features. *Experimental Brain Research*, 97, 177–183.
- Lounasmaa, O. V., Hari, R., Joutsiniemi, S. L., & Hämäläinen, M. (1989). Multi SQUID recordings of human cerebral magnetic fields may give information about memory processes in the human brain. *Europhysics Letters*, 9, 603–608.
- Loveless, N. E., Hari, R., Hämäläinen, M., & Tiihonen, J. (1989). Evoked responses of human auditory cortex may be enhanced by preceding stimuli. *Electroencephalography and Clinical Neurophysiology*, 74, 217–227.
- Lyytinen, H., Blomberg, A. P., & Näätänen, R. (1992). Event-related potentials and autonomic responses to a change in unattended auditory stimuli. *Psychophysiology*, 29, 523–534.
- Maiste, A. C., Wiens, A. S., Hunt, M. J., Scherg, M., & Picton, T. (1995). Event-related potentials and the categorical perception of speech sounds. *Ear and Hearing*, 16, 67–89.
- Makeig, S. (1995). *Effects of attention and stimulus probability on the auditory complex event-related potential*. Manuscript submitted for publication.
- Mäkelä, J., Salmelin, R., Kotila, M., & Hari, R. (1994). Neuro-magnetic correlates of memory disturbance caused by infarction in anterior thalamus. *Society for Neuroscience Abstracts*.
- Mäntysalo, S., & Näätänen, R. (1987). The duration of a neuronal trace of an auditory stimulus as indicated by event-related potentials. *Biological Psychology*, 24, 183–195.
- Massaro, D. W., Cohen, M. M., & Idson, W. L. (1975). Recognition masking of auditory lateralization and pitch judgments. *Journal of the Acoustical Society of America*, 59, 434–441.
- Näätänen, R. (1975). Selective attention and evoked potentials in humans: A critical review. *Biological Psychology*, 2, 237–307.
- Näätänen, R. (1982). Processing negativity: An evoked-potential reflection of selective attention. *Psychological Bulletin*, 92, 605–640.
- Näätänen, R. (1985). Selective attention and stimulus processing: Reflections in event-related potentials, magnetoencephalogram and regional cerebral blood flow. In M. I. Posner & O. S. M. Marin (Eds.), *Attention and performance XI* (pp. 355–373). Hillsdale, NJ: Erlbaum.
- Näätänen, R. (1986). The orienting response theory: A integration of informational and energetical aspects of brain function. In R. Hockey, A. W. K. Gaillard, & M. Coles (Eds.), *Energetics and human information processing* (pp. 91–111). Dordrecht: Martinus Nijhoff.
- Näätänen, R. (1990). The role of attention in auditory information processing as revealed by event-related potentials and other brain measures of cognitive function. *Behavioral and Brain Sciences*, 13, 201–288.
- Näätänen, R. (1991). Mismatch negativity (MMN) outside strong attentional focus: A commentary on Woldorff et al. *Psychophysiology*, 28, 478–484.
- Näätänen, R. (1992). *Attention and brain function*. Hillsdale, NJ: Erlbaum.
- Näätänen, R., & Alho, K. (in press-a). Mismatch negativity: A unique measure of sensory processing in audition. *International Journal of Neuroscience*.
- Näätänen, R., & Alho, K. (in press-b). Event-related potentials (ERPs) in research of selective attention in humans. In R. Johnson, J. C. Baron, J. Grafman, & J. Hendler (Eds.), *Handbook of neuropsychology*, Vol. 9.
- Näätänen, R., & Gaillard, A. W. K. (1983). The N2 deflection of ERP and the orienting reflex. In A. W. K. Gaillard & W. Ritter (Eds.), *EEG correlates of information processing: Theoretical issues* (pp. 119–141). Amsterdam: North Holland.
- Näätänen, R., Gaillard, A. W. K., & Mäntysalo, S. (1978). Early selective-attention effect on evoked potential reinterpreted. *Acta Psychologica*, 42, 313–329.
- Näätänen, R., Jiang, D., Lavikainen, J., Reinikainen, K., & Paavilainen, P. (1993a). Event-related potentials reveal a memory trace for temporal features. *NeuroReport*, 5, 310–312.
- Näätänen, R., & Lyytinen, H. (in press). Mismatch negativity in sleep. In R. Ogilvie & J. Harsh (Eds.), *Sleep onset mechanisms*. Limerick, Ireland: Elsevier Scientific Publishers, Ireland Ltd.
- Näätänen, R., & Michie, P. T. (1979). Early selective attention effects on the evoked potential. A critical review and reinterpretation. *Biological Psychology*, 8, 81–136.
- Näätänen, R., Paavilainen, P., Alho, K., Reinikainen, K., & Sams, M. (1987). The mismatch negativity to intensity changes in an auditory stimulus sequence. In R. Johnson, J. W. Rohrbaugh, & R. Parasuraman (Eds.), *Current trends in event-related brain potential research*. *Electroencephalography and Clinical Neurophysiological Supplement*, 40, 125–131.
- Näätänen, R., Paavilainen, P., & Reinikainen, K. (1989). Do event-related potentials to infrequent decrements in duration of auditory stimuli demonstrate a memory trace in man? *Neuroscience Letters*, 107, 347–352.
- Näätänen, R., Paavilainen, P., Tiitinen, H., Jiang, D., & Alho, K. (1993b). Attention and mismatch negativity. *Psychophysiology*, 30, 436–450.
- Näätänen, R., & Picton, T. W. (1987). The N1 wave of the human electric, & magnetic response to sound: A review and an analysis of the component structure. *Psychophysiology*, 24, 375–425.
- Näätänen, R., Sams, M., & Alho, K. (1986). The mismatch negativity: The ERP sign of a cerebral mismatch process. In C. W. McCallum, R. Zappoli, & F. Denoth (Eds.), *Cerebral Psychophysiology. Electroencephalography and Clinical Neurophysiology*, 38, 172–178.
- Näätänen, R., Sams, M., Järvilehto, T., & Soininen, K. (1983). Probability of deviant stimulus and event-related brain potentials. In R. Sinz & M. Rosenzweig (Eds.), *Psychophysiology: Memory, motivation, and event-related potentials in mental operations* (pp. 397–405). Jena, FRG: VEB Gustav Fischer Verlag.
- Näätänen, R., Simpson, M., & Loveless, N. E. (1982). Stimulus deviance and evoked potentials. *Biological Psychology*, 14, 53–98.
- Näätänen, R., Schröger, E., Karakas, S., Tervaniemi, M., & Paavilainen, P. (1993c). Development of a memory trace for a complex sound in the human brain. *NeuroReport*, 4, 503–506.
- Neisser, U. (1967). *Cognitive psychology*. New York: Appleton-Century-Crofts.
- Nordby, H., Roth, W. T., & Pfefferbaum, A. (1988a). Event-related potentials to breaks in sequences of alternating pitches or interstimulus intervals. *Psychophysiology*, 25, 262–268.
- Nordby, H., Roth, W. T., & Pfefferbaum, A. (1988b). Event-related potentials to time-deviant and pitch-deviant tones. *Psychophysiology*, 25, 249–261.
- Oades, R. D. (1991). Bases for irrelevant information processing in schizophrenia: Room for manoeuvre. *Behavioral and Brain Sciences*, 14, 38–39.
- Paavilainen, P., Alho, K., Reinikainen, K., Sams, M., & Näätänen, R. (1991). Right-hemisphere dominance of different mismatch negativities. *Electroencephalography and Clinical Neurophysiology*, 78, 466–479.
- Paavilainen, P., Cammann, R., Alho, K., Reinikainen, K., Sams, M., & Näätänen, R. (1987). Event-related potentials to pitch change in an auditory stimulus sequence during sleep. In R. Johnson, J. W. Rohrbaugh, & R. Parasuraman (Eds.), *Current trends in event-related brain potential research*. *Electroencephalography and Clinical Neurophysiology Supplement*, 40, 246–255.

- Paavilainen, P., Tiitinen, H., Alho, K., & Näätänen, R. (1993). Mismatch negativity to slight pitch changes outside strong attentional focus. *Biological Psychology*, 37, 23–41.
- Pardo, P. J., & Sams, M. (1993). Human auditory cortex responses to rising versus falling glides. *Neuroscience Letters*, 159, 43–45.
- Pekkonen, E., Jousmäki, V., Partanen, J., & Karhu, J. (1993). Mismatch negativity area and age-related auditory memory. *Electroencephalography and Clinical Neurophysiology*, 87, 321–325.
- Pekkonen, E., Jousmäki, V., Reinikainen, K., & Partanen, J. (in press-a). Automatic auditory discrimination is impaired in Parkinson's disease. *NeuroReport*.
- Pekkonen, E., Jousmäki, V., Könönen, M., Reinikainen, K., & Partanen, J. (in press-b). Auditory sensory memory impairment in Alzheimer's disease measured by event-related potentials. *Electroencephalography and Clinical Neurophysiology*.
- Pekkonen, E., Rinne, T., Reinikainen, K., Kujala, T., Alho, K., & Näätänen, R. (1995). *Aging effects on auditory processing: an event-related potential study*. Manuscript submitted for publication.
- Pietrowsky, R., Fehm, H. L., & Born, J. (1990). An analysis of the effects of corticotropin-releasing hormone (h-CRH), adrenocorticotropin (ATCH), and beta-endorphin on ERPs in humans. In C. M. H. Brunia, A. W. K. Gaillard, & A. Kok (Eds.), *Psychophysiological Brain Research*, Vol. 2 (pp. 106–110). Tilburg: Tilburg University Press.
- Ponton, C. W., & Don, M. (1995). The mismatch negativity in cochlear implant users. *Ear and Hearing*, 16, 130–143.
- Port, R. F. (1991). Can complex temporal patterns be automatized? *Behavioral and Brain Sciences*, 14, 762–764.
- Ritter, W., Deacon, D., Gomes, H., Javitt, D. C., & Vaughan, H. G., Jr. (1995). The mismatch negativity of event-related potentials as a probe of transient auditory memory: A review. *Ear and Hearing*, 16, 51–66.
- Saarienen, J., Paavilainen, P., Schröger, E., Tervaniemi, M., & Näätänen, R. (1992). Representation of abstract attributes of auditory stimuli in the human brain. *NeuroReport*, 3, 1149–1151.
- Sallinen, M., Kaartinen, J., Ruusuvirta, T., & Lyytinen, H. (in press). Auditory event-related potentials during sleep: Mismatch negativity. *Electroencephalography and Clinical Neurophysiology*.
- Sams, M., Hämäläinen, M., Antervo, A., Kaukoranta, E., Reinikainen, K., & Hari, R. (1985a). Cerebral neuromagnetic responses evoked by short auditory stimuli. *Electroencephalography and Clinical Neurophysiology*, 61, 254–266.
- Sams, M., Hari, R., Rif, J., & Knuutila, J. (1993). The human auditory sensory memory trace persists about 10 s: Neuromagnetic evidence. *Journal of Cognitive Neuroscience*, 5, 363–370.
- Sams, M., & Näätänen, R. (1991). Neuromagnetic responses of the human auditory cortex to short frequency glides. *Neuroscience Letters*, 121, 43–46.
- Sams, M., Paavilainen, P., Alho, K., & Näätänen, R. (1985b). Auditory frequency discrimination and event-related potentials. *Electroencephalography and Clinical Neurophysiology*, 62, 437–448.
- Scharf, B., & Houtsma, A. J. (1986). Audition II: Loudness, pitch, localization, aural distortion, pathology. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance*: Vol. 1. *Sensory processes and perception* (pp. 151–160). New York: Wiley.
- Scherg, M., Vajsar, J., & Picton, T. W. (1989). A source analysis of the late human auditory evoked potentials. *Journal of Cognitive Neuroscience*, 1, 336–355.
- Schrodt, A., Cohen, R., Bergman, P., & Hopmann, G. (1992). Automatic (MMN) vs. controlled (P300) processing deficits in the ERPs of schizophrenic patients. *Abstracts of the 10th International Conference on the Event-Related Potentials of the Brain (EPIC X)*.
- Schröger, E. (in press). Deviance-related auditory processing with changes along two stimulus dimensions. *Psychophysiology*.
- Schröger, E. (1994a). An event-related potential study of sensory representations of unfamiliar tonal patterns. *Psychophysiology*, 31, 175–181.
- Schröger, E. (1994b). Attentional capture and mismatch negativity. *Psychophysiology*, 31, S88–89.
- Schröger, E., Näätänen, R., & Paavilainen, P. (1992). Event-related potentials reveal how non-attended complex sound patterns are represented by the human brain. *Neuroscience Letters*, 146, 183–186.
- Shelley, A. M., Ward, P. B., Catts, S. V., Michie, P. T., Andrews, S., & McConaghy, N. (1991). Mismatch negativity: an index of a preattentive processing deficit in schizophrenia. *Biological Psychiatry*, 30, 1059–1062.
- Squires, N. K., Squires, K. C., & Hillyard, S. A. (1975). Two varieties of long-latency positive waves evoked by unpredictable auditory stimuli in man. *Electroencephalography and Clinical Neurophysiology*, 38, 387–401.
- Sokolov, E. N. (1975). The neuronal mechanisms of the orienting reflex. In E. N. Sokolov & O. S. Vinogradova (Eds.), *Neuronal mechanisms of the orienting reflex* (pp. 217–235). Hillsdale, NJ: Erlbaum.
- Tervaniemi, M., Maury, S., & Näätänen, R. (1994a). Neural representations of abstract stimulus features in the human brain as reflected by the mismatch negativity. *NeuroReport*, 5, 844–846.
- Tervaniemi, M., Saarinen, J., Paavilainen, R., Danilova, N., & Näätänen, R. (1994b). Temporal integration of auditory information in sensory memory as reflected by the mismatch negativity. *Biological Psychology*, 38, 157–167.
- Tiitinen, H., May, P., Reinikainen, K., & Näätänen, R. (1994). Attentive novelty detection in humans is governed by preattentive sensory memory. *Nature*, 370, 90–92.
- Trejo, L. J., Ryan-Jones, D. L., & Kramer, A. F. (in press). Attentional modulation of the mismatch negativity elicited by frequency differences between binaurally presented tone bursts. *Psychophysiology*.
- Winkler, I. (1993). *Mismatch negativity: An event-related brain potential measure of auditory sensory memory traces*. Doctoral thesis, University of Helsinki.
- Winkler, I., & Näätänen, R. (1992). Event-related potentials in auditory backward recognition masking: A new way to study the neurophysiological basis of sensory memory in humans. *Neuroscience Letters*, 140, 239–242.
- Winkler, I., Reinikainen, K., & Näätänen, R. (1993). Event-related brain potentials reflect traces of echoic memory in humans. *Perception and Psychophysics*, 53, 443–449.
- Woldorff, M. G., Gallen, C. G., Hampson, S. A., Hillyard, S. A., Pantev, C., Sobel, D., & Bloom, F. E. (1993). Modulation of early sensory processing in human auditory cortex during auditory selective attention. *Proceedings of the National Academy of Sciences of the United States of America*, 90, 8722–8726.
- Woldorff, M. G., Hackley, S. A., & Hillyard, S. A. (1991). The effects of channel-selective attention on the mismatch negativity wave elicited by deviant tones. *Psychophysiology*, 28, 30–42.
- Yabe, H., Tervaniemi, M., Reinikainen, K., & Näätänen, R. (1995). *Mismatch negativity to stimulus omission: Evidence for the temporal window of integration in auditory event perception*. Manuscript submitted for publication.