Absolute Pitch and Event-Related Brain Potentials

M. TERVANIEMI, K. ALHO, P. PAAVILAINEN, M. SAMS, & R. NÄÄTÄNEN
University of Helsinki

An event-related brain potential (ERP) component called mismatch negativity (MMN) is elicited by physically deviant auditory stimuli presented among repetitive, "standard," stimuli. MMN reflects a mismatch process between sensory input from the deviant stimulus and a short-duration neuronal representation developed by the standard stimulus. The MMN amplitude is known to correlate with pitch-discrimination performance. The purpose of the present study was to investigate whether the MMN is different in absolute pitch (AP) possessors and nonpossessors. ERPs were recorded from AP and non-AP groups, which were matched with regard to musical training.

It was found that deviant stimuli differing from standard tones by a quartertone or a semitone elicited an MMN irrespective of whether the stimulus was located *on* (white key/black key) or *off* the Western musical scale. These results were obtained with both sinusoidal and piano tones. The MMN was larger and earlier when the stimuli were piano tones than when they were sinusoidal tones and when the standard-deviant difference amounted to a semitone rather than a quartertone. However, differences between the groups were not found in auditory information processing reflected by the MMN component of the ERP. In the light of the earlier MMN results showing a close correlation between the MMN and pitch-discrimination accuracy, it might be concluded that pitch discrimination and identification are based on different brain mechanisms. In addition, the differences in the MMN amplitude and latency between sinusoidal and piano tones might be interpreted as suggesting that sensory memory traces, as reflected by the MMN, are capable of storing information of very complex sound structures also.

Introduction

ABSOLUTE PITCH

Absolute pitch (AP) is the ability to identify or produce a tone, for example, in terms of Western musical scale without hearing a reference tone. In the psychology of music, the AP phenomenon has inspired debates

and experiments about its existence, significance, etiology, relationships to other musical abilities, and about the memory and coding functions involved (Bachem, 1937, 1940, 1954; Brady, 1970; Cuddy, 1967, 1970; Klein, Coles, & Donchin, 1984; Miyazaki, 1988, 1989, 1990; Neu, 1947; Petran, 1932; Révész, 1953; Siegel, 1974; van Kraevelen, 1951; Ward, 1963a, 1963b; Ward & Burns, 1982; Zatorre & Beckett, 1989).

In the recent literature, the AP is most often thought to be an effect of early training in instrument playing (cf. Takeuchi & Hulse, submitted), in contrast to earlier theories, which emphasize its hereditary nature (Bachem, 1940). The more recent view that stresses learning is supported by findings showing that the pitch-naming accuracy of AP possessors depends on the amount of practice they have received with the tones. First, when the tones to be named are produced with instruments that have unfamiliar timbres, the AP possessors respond more slowly and make more errors (Miyazaki, 1989; Lockhead & Byrd, 1981). Second, the tones from the middle register (around C_4) are recognized faster and more accurately than tones from extreme pitch registers; this is also the case with white-key pitches (nonflat and nonsharp tones) when compared with black-key pitches (Miyazaki, 1989, 1990; Takeuchi & Hulse, 1991). It has been concluded that because of the more extensive training with white-key tones from the middle register, these tones are most easily named.

The AP seems to be an ability to categorize tones into familiar classes and to remember the names of the classes, rather than to remember the exact frequencies of tones (Siegel, 1974). The importance of correct categorization in terms of the two-component theory of pitch perception (Révész, 1953) is obvious when we take into account that the most common errors in pitch naming that AP possessors make are those of one octave (cf. Klein et al., 1984). Thus they can recognize the chroma (the name of the tone) but make errors in the height of the tone, in its octave. The relation of the AP to pitch-discrimination accuracy has been controversial: some results indicate correlations between these abilities (Oakes, 1955), whereas some others do not (Sergeant, 1969). Neu (1947) went so far as to claim that absolute pitch is the utmost form of pitch discrimination.

EVENT-RELATED POTENTIALS IN RESEARCH
OF MEMORY FUNCTIONS

Recording of event-related potentials from the human scalp provides a tool for investigating brain mechanisms involved in the processing of auditory events (e.g., Näätänen, 1990) including those constituting music (e.g., Klein et al., 1984; Lang, Nyrke, Ek, Aaltonen, Raimo, & Näätänen, 1990; Petsche, Lindner, Rappelsberger, & Gruber, 1988). Event-related

potentials (ERPs) are small changes in the electrical brain activity (electroencephalogram, EEG) caused by the processing of a stimulus. They can be separated from the other ongoing electrical activity by averaging usually hundreds of EEG epochs that follow stimulus presentation (Regan, 1989). Thus activity that is not time locked to stimulus presentation, and therefore is random in nature, is canceled, whereas activity related to stimulus processing (i.e., ERP) remains. An ERP consists of a series of positive and negative components occurring during a few hundred milliseconds after stimulus onset. These components are generated by the activation of different brain areas (Näätänen & Picton, 1987).

Klein et al. (1984) found that in AP possessors an ERP component called the P300 (a positive wave peaking around 300–500 msec from stimulus onset) is absent or strongly diminished in the response to targets in auditory discrimination tasks, whereas in visual discrimination tasks the response included a normal P300. In their non-AP control group, the P300 was elicited in both types of discrimination tasks. The authors concluded that the P300 is a manifestation of working memory, with AP possessors being able to discriminate auditory stimuli without fetching and comparing representations for novel stimuli.

The ERP component called the *mismatch negativity* (MMN; Näätänen, Gaillard, & Mäntysalo, 1978; for a review, see Näätänen, 1992) can be used to investigate sensory memory. It has been suggested that the sensory information of the repetitive physical features of the auditory stimulation is stored in the auditory cortex in a short-duration neuronal memory trace with which each auditory input is compared. If a stimulus whose physical parameters (such as frequency or intensity) do not correspond to those encoded in the trace is delivered during the existence of this trace, a mismatch process generating the MMN occurs.

The MMN can be experimentally studied with the so-called *oddball paradigm*, where frequent standard stimuli (for example 1000-Hz tones) and infrequent deviant stimuli (e.g., 1016-Hz tones) are presented with short intervals in long, randomized sequences (e.g., Sams, Paavilainen, Alho, & Näätänen, 1985). The MMN is elicited by a deviant tone, and it peaks 100–200 msec after their onset.

Physical stimulus features stored in the memory traces reflected by the MMN include stimulus frequency, intensity, duration, the location of the sound source, and the rise time of the sound (Lyytinen, Blomberg, & Näätänen, 1992; Näätänen et al., 1978; Näätänen, Paavilainen, Alho, Reinikainen, Sams, 1987, 1989; Näätänen, Paavilainen, & Reinikainen, 1989; Paavilainen, Karlsson, Reinikainen, Näätänen, 1989; Sams, et al., 1985). The phonetic structure of a stimulus is also stored in the neuronal memory trace. For example, the phoneme /ba/ among phonemes /ga/ elicits an MMN (Sams, Aulanko, Aaltonen, & Näätänen, 1990; see also

Aaltonen, Niemi, Nyrke, & Tuhkanen, 1987). In addition, Nordby, Roth, & Pfefferbaum (1988) showed that temporal changes in stimulus presentation, for example, stimulus repetition in a sequence of two alternating tones, can elicit the MMN. This mismatch process seems to be automatic, occurring even when attention is not focused on the auditory stimuli when, for example, the subject concentrates on reading a book or on performing a demanding visual task (e.g., Alho, Woods, Algazi, & Näätänen, 1992).

The MMN amplitude correlates with pitch-discrimination performance. Lang et al. (1990) divided his subjects into three groups on the basis of pitch-discrimination accuracy as determined by the Seashore pitch-discrimination test. Significant differences in the MMN amplitudes were found between the groups. With good discriminators, a distinct MMN was observed when the difference between the standard (698 Hz) and deviant stimuli was 19 Hz, whereas for poor discriminators, a difference of 99 Hz was needed. Also, it has been shown that the MMN develops gradually as the subject learns to detect small frequency changes in a complex stimulus pattern (Näätänen, Schröger, Karakas, Tervaniemi, & Paavilainen, submitted). The results thus suggest that the MMN might reflect the development of the neural stimulus representation.

The purpose of the present study was to investigate whether AP and non-AP possessors differ in the MMN, which according to the aforementioned studies (Lang et al., 1990; Näätänen et al., in preparation) indicates discrimination accuracy. Stimulus frequencies were selected on the basis of their location on the musical scale (either *on* the scale; white key/black key or *off* the scale). In addition, there were two types of stimuli, with one type per block: sinusoidal tones and synthesized piano tones. These stimulus parameters were selected in view of the above-mentioned disparities in AP possessors in the processing of stimuli of different timbres and different locations on the musical scale.

Methods

SUBJECTS

Eight subjects with AP formed the AP group. A control group was formed by eight subjects with equally long musical training but no AP. An academic degree in playing one or more instruments was used as the criterion for musical training. All but one subject had received a degree in music theory too. To confirm the group division, the subjects' pitch-naming performance was tested (after the ERP recordings) by presenting 50 randomly chosen synthesized piano tones between C_2 and E_6 (the duration of the tape-recorded test tones was 1.5 sec, presented with 4-sec interstimulus intervals through headphones). Subjects were instructed to write down the name and the octave of the tones presented. The response was labeled correct when it was correct with regard to both name *and* octave. Subjects were paid for their participation.
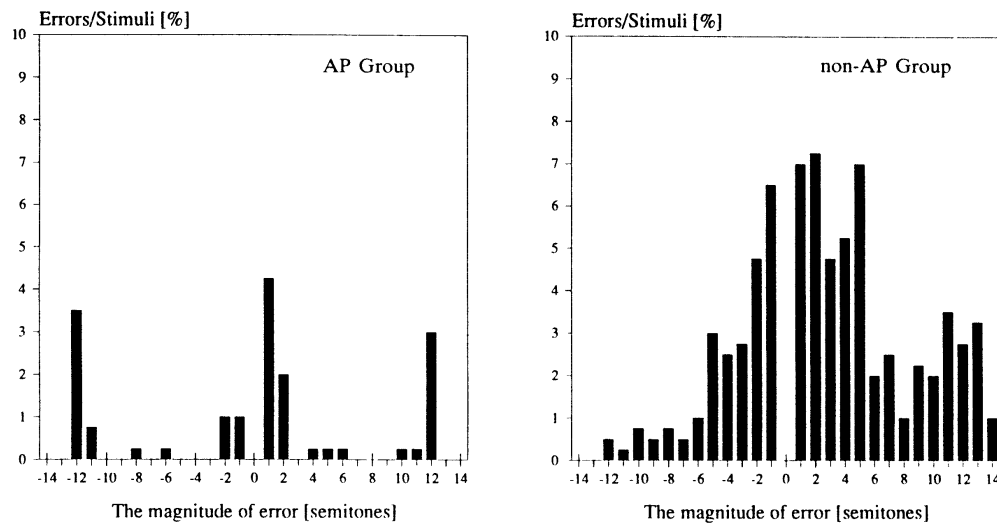
Errors/Stimuli [%]   Errors/Stimuli [%]

The magnitude of error [semitones]   The magnitude of error [semitones]

Fig. 1. Performance in the pitch-naming test. (left) Absolute pitch (AP) group: correct responses, 81.5% ($n = 326$); errors larger than 14 semitones or no response (outside the diagram), 0.5% ($n = 2$). (right) Non–absolute pitch (non-AP) group: correct responses, 9% ($n = 36$); errors larger than 14 semitones or no response (outside the diagram), 19% ($n = 77$).

The AP subjects were 20–35 years old (mean, 25 years; five men, three women) and had started playing some musical instrument at the average age of 6 years. Seven of these subjects already worked, or were starting to work, as professional musicians. Their AP had been noticed at the mean age of 9 years. Their mean performance in the pitch-naming test was 81.5% correct (range, 52–98%; for the distribution of errors, see Figure 1, left).

The non-AP subjects were 20–26 years old (mean, 23 years; two men, six women) and had started to play some instrument at the mean age of 7 years. Five of them worked, or were intended to work, as professional musicians. Their mean performance in the pitch-naming test was 9% correct (range, 2–22%; for the distribution of errors, see Figure 1, right).

STIMULI

There were two types of stimuli: piano tones and sinusoidal tones. *Piano* tones were synthesized piano tones with an Akai 900 synthesizer (piano A tones; shortened with the MacPlus Sound Designer program). The other stimulus type was simple *sinusoidal* tones (without upper harmonics). The stimuli were recorded on audio tape. They were presented binaurally through headphones at an intensity of 75 dB SPL in blocks of 500 stimuli. The stimulus duration was 150 msec (with rise and fall times each of 10 msec) and the interstimulus interval (onset-to-onset) was 540 msec.

Four experimental conditions, as listed in Table 1, were included. In all conditions, stimuli of two frequencies were presented in random order: standard tones with a probability of 0.9 and deviant tones with a probability of 0.1. Their locations on the scale were as follows: in the quartertone condition c/c+ (262/269 Hz), the standard stimulus (c) was *on* the scale and the deviant stimulus (c+) *off* the scale (between c and c♯). In condition c−/c (254/262 Hz), the magnitude of stimulus deviation was also a quartertone but now the standard stimulus (c−) was *off* the scale and the deviant stimulus (c) *on* the scale. In the semitone condition c/c♯ (262/277 Hz), the magnitude of stimulus deviation was a semitone and both stimuli were on the scale, whereas in the semitone condition c+/c♯+ (269/285 Hz), neither was on the scale.

TABLE 1

The Pitch Classes and Frequencies of the Standard
and Deviant Stimuli Used

Condition	Standard Stimuli		Deviant Stimuli	
	Pitch Class	Frequency (Hz)	Pitch Class	Frequency (Hz)
Quartertone deviation				
c/c+, standard on, deviant off scale	c	262	c+	269
c−/c, standard off, deviant on scale	c−	254	c	262
Semitone deviation				
c/c♯, standard and deviant on scale	c	262	c♯	277
c+/c♯+, standard and deviant off scale	c+	269	c♯+	285

NOTE. c+ designates the tone between C and C♯, c− the tone between B and C, and c♯+ the tone between C♯ and D.

During the experiment, the subject was sitting in an acoustically and electrically shielded room. Subjects were instructed to read a self-selected book, to pay no attention to auditory stimuli, and to avoid eye or muscle movements. The four conditions were presented in counterbalanced order, twice with both stimulus types. After each condition (lasting about 4 min), there was a short break, and in the middle of the experiment a longer one.

EEG RECORDING AND ANALYSIS

The EEG was recorded (bandpass, 0.1–100 Hz; −3 dB points; sampling rate 200 Hz; analysis period 450 msec) with Ag-AgCl electrodes at four scalp locations attached to the midline: F_{pz} (on the forehead), F_z (over the frontal area), C_z (over the vertex), and P_z (over the parietal areas). Two electrodes were placed over the left and right frontal hemispheres (F_3 and F_4). The electro-oculogram (EOG) was recorded with one electrode from the outer canthus of the right eye to eliminate artifacts caused by horizontal eye movements. The nose served as a reference for all electrodes.

The EEG was amplified and digitized, and stored to computer disk. The ERPs were averaged separately for standards and deviants in each condition. After averaging, the ERPs were filtered with a 30-Hz low-pass (FFT) filter. Epochs contaminated by extracerebral artifacts, defined at all electrodes as EEG change during an epoch exceeding 150 μV, and caused usually by blinks, eye movements, or muscle activity, were omitted. Grand-average ERPs (averaged over all subjects) were formed separately for the AP and non-AP groups. Difference wave forms (grand-average ERPs to standard stimuli subtracted from those to deviant stimuli) were calculated in order to measure the MMN latency and amplitude.

The MMN peak latency was measured in the individual difference waves as the largest negative peak between 50 and 250 msec after stimulus onset. The MMN amplitude was measured as the mean amplitude at F_z during the 60-msec time window centered at the largest negative peak with reference to the 25-msec prestimulus baseline. In the following, only the F_z data will be reported because the MMN was largest at this electrode and no interhemispheric differences were found.
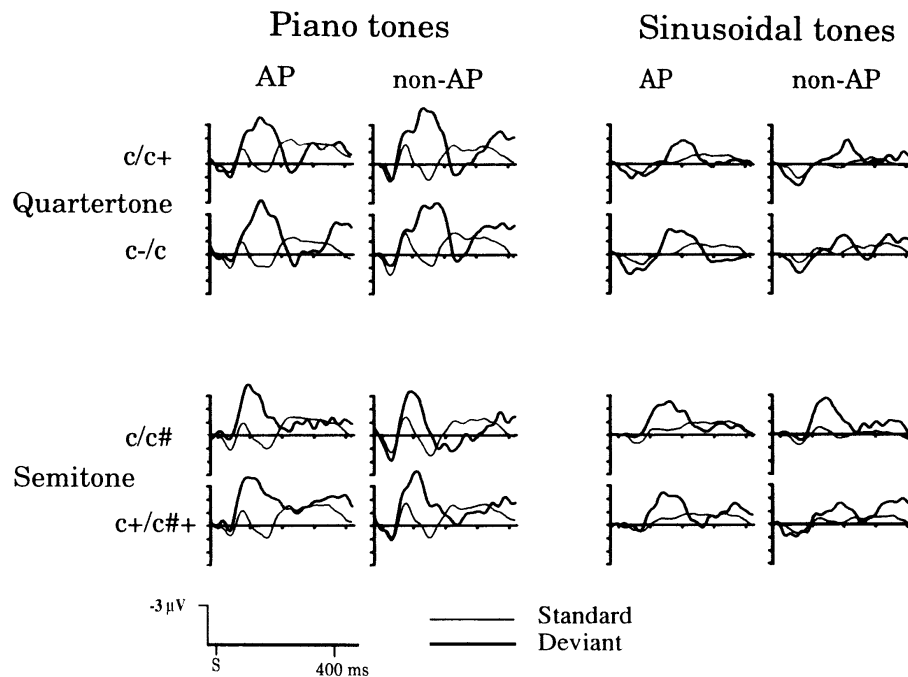
Piano tones Sinusoidal tones

Fig. 2. The event-related potentials (ERPs) of the absolute pitch (AP) and non–absolute pitch (non-AP) groups to the piano and sinusoidal tones in different conditions at the F_z electrode (conditions shown on the left). Thin line represents ERPs to standard stimuli; thick line, ERPs to deviant stimuli.

Results

The grand-average ERPs at the F_z electrode over the frontal areas to standard and deviant stimuli are shown in Figure 2. It can be seen that deviant stimuli elicited a sizeable MMN, which peaks at 100–250 msec from stimulus onset.

The difference waveforms at the F_z electrode for the AP and non-AP groups are presented in Figure 3. With the sinusoidal tones in the quartertone conditions (c/c +, c−/c), the MMN peaks can be seen at 150–250 msec after stimulus presentation, whereas in the semitone conditions (c/c♯, c+/c♯ +) its peak latency is as short as 100–200 msec. With the piano tones, these latencies are in general shorter: in quartertone conditions, the MMN peaks at 100–200 msec, and in the semitone conditions at 75–150 msec.

The MMN reached its amplitude maximum over the frontal area. This amplitude differed significantly from zero at F_z in both subject groups and in all stimulus conditions ($t = 2.133$–7.802, $p < .05$–$.001$; one tailed t-tests). The MMN amplitude was significantly larger for the piano than
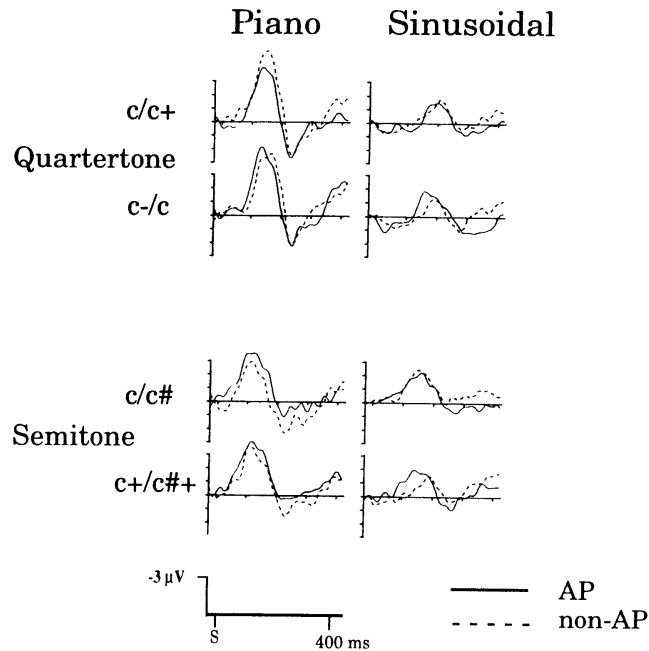
Fig. 3. The difference waveforms of the absolute pitch (AP) group and the non–absolute pitch (non-AP) group to the piano and sinusoidal tones in different conditions at the F_z electrode. (ERPs to the standard stimuli are subtracted from those to the deviants.) The continuous lines represent difference waveforms of the AP group; dashed lines, difference waveforms of the non-AP group.

sinusoidal tones [three-way analysis of variance, factors: group, stimulus type, stimulus condition; $F(1,14) = 43.12$, $p < .0001$].

In a further statistical analysis of the data presented in Table 2, the MMN latency at F_z was found to be significantly shorter for the piano than sinusoidal tones in both subject groups and all conditions [$F(1,14) = 59.30$, $p < .0001$]. In addition, the MMN latency was significantly shorter in the semitone than quartertone conditions [two-way analysis of variance, factors: group, deviation; piano tones: $F(1,14) = 16.46$, $p < .001$, sinusoidal tones: $F(1,14) = 5.88$, $p < .03$].

There were no significant MMN differences between the AP and non-AP groups with respect to the stimulus type or condition.

Discussion

The results showing that the MMN to frequency change is very similar for AP and non-AP possessors (with similar musical backgrounds) suggest that auditory information processing reflected by the MMN does not differ between these groups. In view of Lang et al.'s (1990) results demonstrating a strong correlation between discrimination accuracy and the

TABLE 2
MMN Amplitudes and Latencies at the
Midfrontal (F$_z$) Electrode

Tones	Amplitude (μV)		Latency (msec)	
	AP	Non-AP	AP	Non-AP
Sinusoidal				
c/c+	-1.42 (0.67)	-1.50 (0.57)	198 (9)	185 (12)
c−/c	-1.74 (0.73)	-1.24 (0.57)	179 (16)	183 (14)
c/c♯	-1.92 (0.34)	-2.46 (0.57)	166 (11)	155 (16)
c+/c♯+	-1.84 (0.45)	-1.78 (0.23)	144 (11)	192 (11)
Piano				
c/c+	-3.48 (0.74)	-4.71 (0.94)	148 (7)	155 (8)
c−/c	-4.31 (0.64)	-4.37 (1.09)	146 (9)	161 (10)
c/c♯	-3.39 (0.66)	-2.85 (0.76)	113 (9)	129 (17)
c+/c♯+	-3.47 (0.72)	-3.28 (0.67)	138 (8)	129 (13)

NOTE. The MMN amplitude was measured as a mean amplitude during the 60-msec time window centered at the most negative peak of the difference waveform at F$_z$. (The standard error is given in parentheses.)

MMN amplitude as well as latency, it may be concluded that pitch discrimination and naming are based on different brain mechanisms.

Because, in the AP group, no differences were found in the MMN elicitation with respect to the stimulus location being either on or off the scale, it may be suggested that the MMN reflects stimulus processing on the acoustical, rather than categorical, level. This is consistent with the recent result of Sharma, Kraus, McGee, Carrell, & Nicol (in press), which is interpreted as showing no categorization effect of the MMN to phonetic stimuli when standard and deviant stimuli were presented across or within phonetic categories.

The MMN latency was shorter and its amplitude larger for the piano than for the sinusoidal tones in both subject groups. In the case of harmonic complex tones, the MMN is probably composed of contributions from individual mismatch processes occurring in parallel for all harmonics. This would explain the stronger MMN process as being elicited by a larger amount of deviating elements.

In the present experiment, subjects were instructed to read a book and to ignore the auditory stimuli. In these conditions, the auditory long-term representations that AP subjects presumably have for identifiable frequencies seemed to remain passive (Cowan, 1988; Cowan, Winkler, Teder, & Näätänen, in press) and not affect the sensory processing reflected by the present electrophysiological measurements. The activation of the long-term representations of identifiable frequencies might require attentive listening to the tones.

In general, the MMN observed in the present study resembled those elicited in previous experiments. Its amplitude was frontally largest in all conditions and with both stimulus types. In addition, larger physical differences between standard and deviant stimuli (semitone versus quartertone) shortened the MMN peak latency, and with the sinusoidal tones, the MMN amplitude was larger with the semitone than the quartertone deviation. In contrast, with the piano tones, the semitone and quartertone deviations elicited MMNs with very similar amplitudes. Thus with these stimuli, the MMN amplitude seemed to reach a plateau with growing magnitude of deviation, being no more able to reflect it. The same was observed by Sams et al. (1985), who found that MMN amplitude was larger for the 1016-Hz than for the 1008-Hz deviant stimuli (the standard stimulus being 1000 Hz) but did not increase further when the deviant stimulus was 1032 Hz.

In summary, with AP and non-AP groups, which were matched with regard to musical training, differences were not found in auditory information processing reflected by the MMN component of the ERP. In the light of the earlier MMN results showing a close correlation between the MMN and pitch-discrimination accuracy, it might be concluded that pitch discrimination and identification are based on different brain mechanisms. In addition, the differences in the MMN amplitude and latency between sinusoidal and piano tones might be interpreted as suggesting that sensory memory traces, as reflected by the MMN, can store information of also very complex sound structures.

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