Chapter 7

Hearing Impairment in Professional Musicians and Industrial Workers — Profession-Specific Auditory Stimuli Used to Evoke Event-Related Brain Potentials and to Show Different Auditory Perception and Processing

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Additional information is available at the end of the chapter

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Abstract

Hearing impaired professional musicians or industrial workers often report that they were able to identify mistuned chords in a music piece or even slight changes in the noise of their machines (usually > 100 dB SPL) though they were handicapped in listening tasks in daily routine.

In order to assess central processing of acoustic stimuli, we analyzed auditory evoked potentials (AEP) and EEG spectra after stimulation with work-related auditory stimuli in healthy controls, in hearing impaired musicians or hearing impaired workers from the beverage industry. Stimuli were series of in-tune or mistuned synthetic piano chords or the original machine noise the workers heard in daily routine and the same noise with disturbing signals.

Professional musicians identified the mistuned stimuli and the AEP differed significantly. The workers recognized the disturb signals. In both groups the spectral analysis confirmed a frequency shift towards higher alpha frequencies and an altered spatial distribution of the EEG frequencies during presentation of the disturb signals.

We assume that professionalism causes learning of typical auditory stimuli that is important for auditory processing after hearing impairment. AEP component analysis and spectral analysis of the EEG are important tools to objectify this processing, in particular in hearing impaired employees.

Keywords: Auditory evoked potential, Mismatch negativity (MMN), Hearing impairment, Permanent threshold shift (PTS), Occupational disease

1. Introduction

The mismatch negativity component (MMN) of auditory evoked event-related potential can be elicited by deviant stimuli inserted into a follow-up of identical sounds [1]. See for review [2]. In the past, numerous studies had been performed in which changed attributes of the stimuli, such as decrement in duration [3], changes in frequency [4], or changed stimulus intensity [5], were used to differentiate between standard and deviant stimuli. MMN to musical stimuli has been investigated for a long time. It was shown that MMN was caused by a timbre change [6,7]. In a later study, it was shown [8] that comparison of MMN to omitted tones in a series of sine-wave tone pips could be used to differentiate between musicians and non-musicians. Violation of harmony rules elicited large MMN in the fronto-central cortex areas [9]. Slightly mistuned chords produced MMN in professional violinists, but not in non-musicians [10]. Similarly, larger and earlier MMN to rhythm variations were observed in jazz musicians than in non-musicians [11].

An earlier study of our group raised the issue that hearing-impaired professional musicians were able to play their instruments in the orchestras and to perform without problems when they were trained for years, regardless of their permanent threshold shift (PTS) [12]. Interestingly, those musicians reported on hearing problems when watching TV or if they wanted to have conversation in a noisy environment (party-noise effect). To our knowledge, there are only few studies about musicians dealing with the effects of occupational noise and central compensation after hearing damage. Therefore, we want to test whether differences exist in auditory event-related potentials (AEP) (amplitudes and latencies) and/or in MMN reflecting the sound processing while comparing normal hearing people and musicians (normal hearing and hearing impaired). The new aspect in our study is the use of typical musical stimuli, i.e., in-tune and mistuned chords. We assumed that professional musicians should be trained to these stimuli regardless whether they have normal hearing or not.

There is some evidence for the assumption that ongoing training of professional musicians would produce changes in the central processing of musical auditory signals since an earlier study did not find different neural generators for MMN while comparing musicians and non-musicians, but found typical differences in MMN between both groups after omitted tone pips [8]. From other data, it was supposed that ongoing professional training could result in a more accurate tuning of frequency-specific neurons in musicians [10]. Professional musicians are considered to be a model for cortical plasticity caused by ongoing musical training [13-17]. In a review [18], it was summarized that top-down and bottom-up plasticity exists in the auditory cortex, as well as in other somatosensory areas of the brain. This was supported by a recent

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study [19] that showed that the posterior medial cortex is involved in processing of melodic and harmonic information. If ongoing musical training participates in this process, it would be interesting to see whether a hearing deficit in trained professional musicians would interfere with, e.g., an improved tuning function or with the recognition of wrongly tuned sounds.

The present experiments investigated whether MMN could be detected in professional musicians, non-musicians, or industrial workers without formal musical training when typical musical stimuli (C-chords) were presented in the oddball-design. To get better information over the whole range of audibility, we applied the stimuli both in the mid-frequency and in the high-frequency range. We analyzed the amplitudes and latencies of the first positive and negative components of the AEP. We looked further for differences in the MMN between the three investigated groups. In another series of experiments, we tested with the same paradigm, whether MMN to mistuned high-frequency stimuli could still be observed in hearing-impaired professional musicians with a PTS in the high-frequency range between 3.000 Hz and 8.000 Hz. To evaluate to what extent the subjects were annoyed by the mistuned chords, we analyzed the EEG frequency activity in the interstimulus intervals and additionally looked for changes in heart frequency. To check, whether a long-lasting professional training might have induced a learning process for specific sounds, we repeated the EEG and heart frequency analysis in the group of hearing-impaired workers and presented them slightly disturbed machine noise they usually had heard in their daily working routine.

Hypotheses:

1. Ongoing professional training of musicians or of workers to listen to specific sounds either while performing music or watching machine sounds changes the central sound processing. These changes in AEP can be used to differentiate between untrained and trained persons.

2. The ongoing training to profession-specific sounds enables the trained person to recognize even slight deviations. The recognition is reflected by specific late components of the AEP, even when the person was not aware of the deviated stimulus.

3. The learned specific sounds could even be recognized when sound perception is disturbed by a permanent hearing impairment (PTS). External stimuli that were not trained would not be recognized even though they would be presented in the same sound intensity.

2. Materials and methods

2.1. Proband groups

Normal hearing and hearing-impaired non-musicians, aged 16 to 30 years

A group consisting of 16 members of the Medical Faculty of Jena (mean age 21.3 years) who had no hearing deficits, and who did not perform music regularly and never had formal training in music was categorized as non-musicians. The participants were all right-handed.

The hearing-impaired group (10 age-matched participants) had a hearing deficit (PTS) of about 20 dB SPL in the frequency range from 3.000 Hz to 8.000 Hz.

Normal hearing and hearing-impaired professional musicians, aged 28 to 68 years

In this part of the study participated 15 professional normal hearing musicians (mean age 41.4 years) who were employed at three German orchestras. The instrument groups were violins, trombones, oboes, bassoons, cellos, violas, and contrabasses. A second group of 10 professional musicians from the same three orchestras (mean age 48.1 years) had a hearing deficit (PTS) of more than 30 dB in frequencies larger 3 kHz. These 10 musicians played violins, contrabasses, bassoon, cello, trombones, and oboe.

Hearing-impaired industrial workers, aged 38 to 63 years

In this part of the study participated 20 industrial workers from a brewery who worked on bottle washing or bottle filling machines. Their hearing loss (PTS) of more than 20 dB SPL in the frequency range from 3.000 Hz to 8.000 Hz was officially recognized as an occupational disease. The workers were aged 38 to 63 years and had never had formal musical training or played any kind of music. All experiments were performed without hearing aids.

2.2. Study design

The study was approved by the local ethics committee of the University of Jena. All participants gave informed consent to this study and received monetary compensation for their participation. In a questionnaire, the participants were asked for their age; musical experiences, i.e., duration of employment in the orchestra or attending music school, instruments that are or were played, duration of training time per week, and the use of hearing protectors; occurrence of tinnitus; occurrence of ear, nose, and throat diseases; and hereditary ear diseases in the family. We also asked for noisy leisure time activities. The workers were asked similar questions with special respect for noise exposition per working shift. The hearing ability of the right and left ears in each participant was tested by means of a high frequency audiometer (Grahnert Präcitronic MA 22; Dresden, Germany, combined with a headphone HDA-200; Sennheiser, Hannover, Germany) and by measuring the otoacoustic emissions (DPOAE/TEOAE) (Madsen, Denmark). Details were given by our group in the literature [12].

To study the perception of auditory stimuli, we recorded MMN using the classical ac-EEG technique. Participants were seated comfortably with closed eyes. They listened to the stimuli that were presented via loudspeakers in the free field mode and were instructed only to listen relaxed and to avoid attention or any reaction to the stimuli to minimize artifacts caused by movements.

The ac-EEG was recorded from 32 electrodes (Figure 1) positioned according to the international 10/20 system over frontal, central, temporal and parietal brain areas of both hemispheres using the standardized Easy-Cap device (Easy Cap GmbH, Herrsching-Breitbrunn, Germany). A linked-mastoid electrode served as a reference. Impedance was maintained below 5 kOhm. An electrode at the forehead was used as a ground. The electrooculogram was recorded for rejection of artifacts (two electrodes above and below the eye, one electrode lateral to the eye).

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The EEG was recorded with the Brain Products recording system (Brain Products GmbH, Gilching, Germany). The bandpass ranged from 0.1 Hz to 250 Hz. The amplified signals were digitized at a 5.000 Hz sample rate and analyzed off-line. The electrocardiogram was recorded for a beat-to-beat frequency analysis.

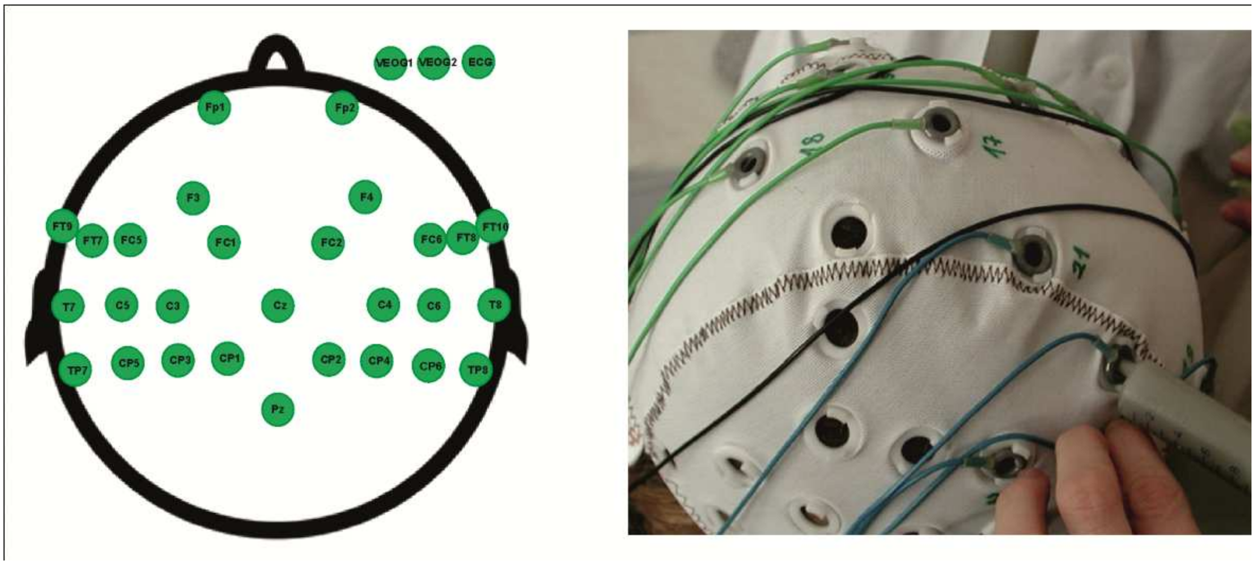

Figure 1. The left panel shows the typical electrode positions at the cap that were used in this study. Two additional reference electrodes were placed at the mastoids and as a ground electrode, the FPC position was used. To extract artifacts by eye movements, the VEOG was recorded with two electrodes. For analyzing the heart rate, the electrocardiogram in the Einthoven triangle was recorded (symbolized by the ECG marking). The right panel shows the Easy Cap device on the head while fixing the electrodes.

2.3. Auditory stimuli

Stimuli were pure C1-major chords, C3 chords, and respective mistuned chords in a classical oddball paradigm. The mistuned chords were generated by a synthesizer (variation +50 cent of the middle tone for the C-major chord, and variation +12 cent for the C3 chord) (Figure 2). A frequency and spectrogram analysis was performed to assure that the mistuned chords were in the same frequency range and had a similar intensity (integrating-averaging Sound Level Meter, type 118, class 1; Norsonic, Lierskog, Norway). Whereas the +50 cent variation was easy to differentiate from correct tunes, the +12 cent variation was difficult to discern for all non-trained listeners.

Stimuli were stored on a PC and presented in a free-field mode via the Presentation software (Presentation V9.12, NBS, Berkeley, CA) via two active loudspeakers as shown in Figure 3.

A recording session consisted of four trains per 200 single stimuli each. The participants listened with closed eyes to two trains of C1-major chords and to two trains of C3 chords. Parent and deviant stimuli were presented randomly in a 4:1 order and at randomized interstimulus intervals lasting from 2 to 6 seconds. We defined three different paradigms of stimulus occurrence: paradigm 1 had 150 normal and 50 mistuned C1-major chords, paradigm

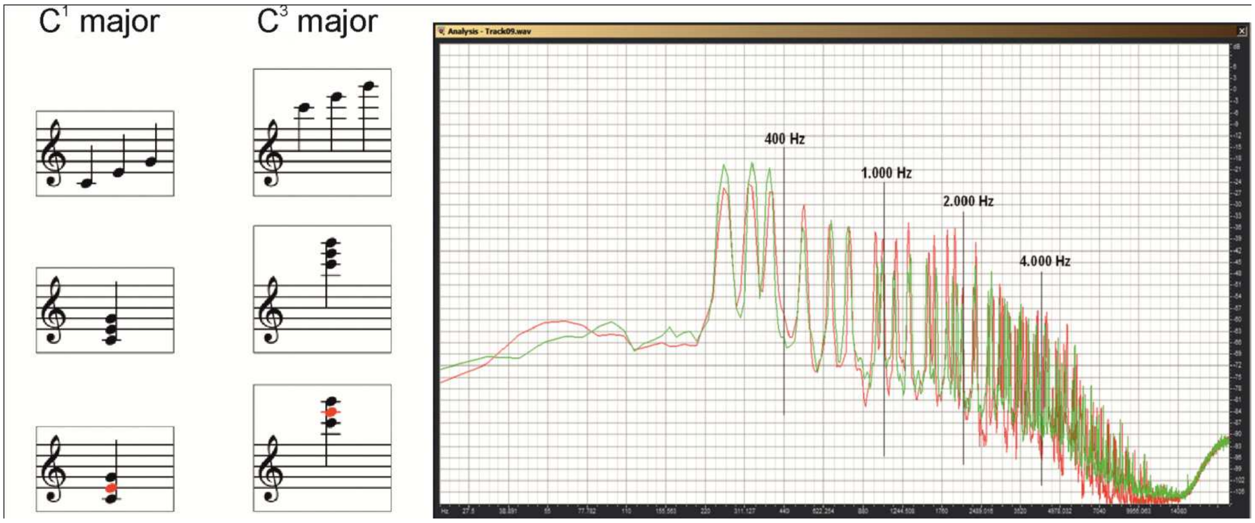

Figure 2. Design of the musical chords produced with a computer synthesizer. The C1 major (ca. 400 Hz) were the low frequency stimuli and the C3 major (ca. 1300 Hz) the high frequency stimuli. For mistuning, the middle tone E was modified (marked with red in the lower panels on the left side). The diagram on the right shows a screenshot with the intensities of both stimuli in a frequency spectrum. Note that there is no significant difference in intensity between the normal and mistuned stimuli.

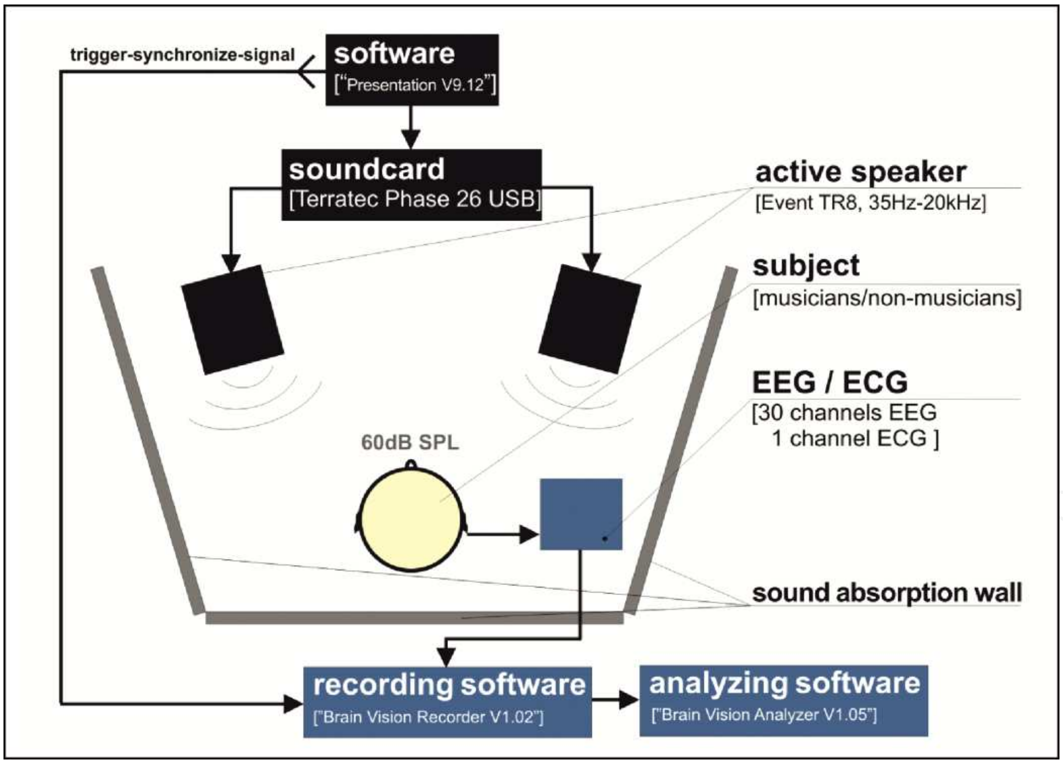

Figure 3. Schematic diagram of sound presentation and data recording setup in this study.

2 150 mistuned and 50 normal C1-major chords, and paradigm 3 150 normal and 50 mistuned C3-major chords. Non-musicians and professional musicians listened to all three paradigms. The stimulus intensity was set at 65 dB SPL.

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The industrial workers listened only to musical stimuli in the paradigms 1 and 2 with the same number of stimuli. For testing the industrial workers with specific sounds they were trained to listen to we recorded samples of the machine noise as parent stimuli and interrupted this machine noise with short high-pitched whistles or with very short intervals of random white noise (deviant stimulus). Both types of stimuli were presented in an oddball paradigm with similar time intervals at an intensity of 65 dB SPL.

2.4. Data analysis

Trials contaminated with artifacts (e.g., contractions of mimic muscles or eye movements) were excluded from further analysis. The AEP in the EEG were evaluated using the BrainVision Analyzer 2 (Brain Products, Munich, Germany). We observed a 512 ms time range with a 50 ms pre-stimulus interval. A set of raw EEG data from all electrodes is presented in Figure 4.

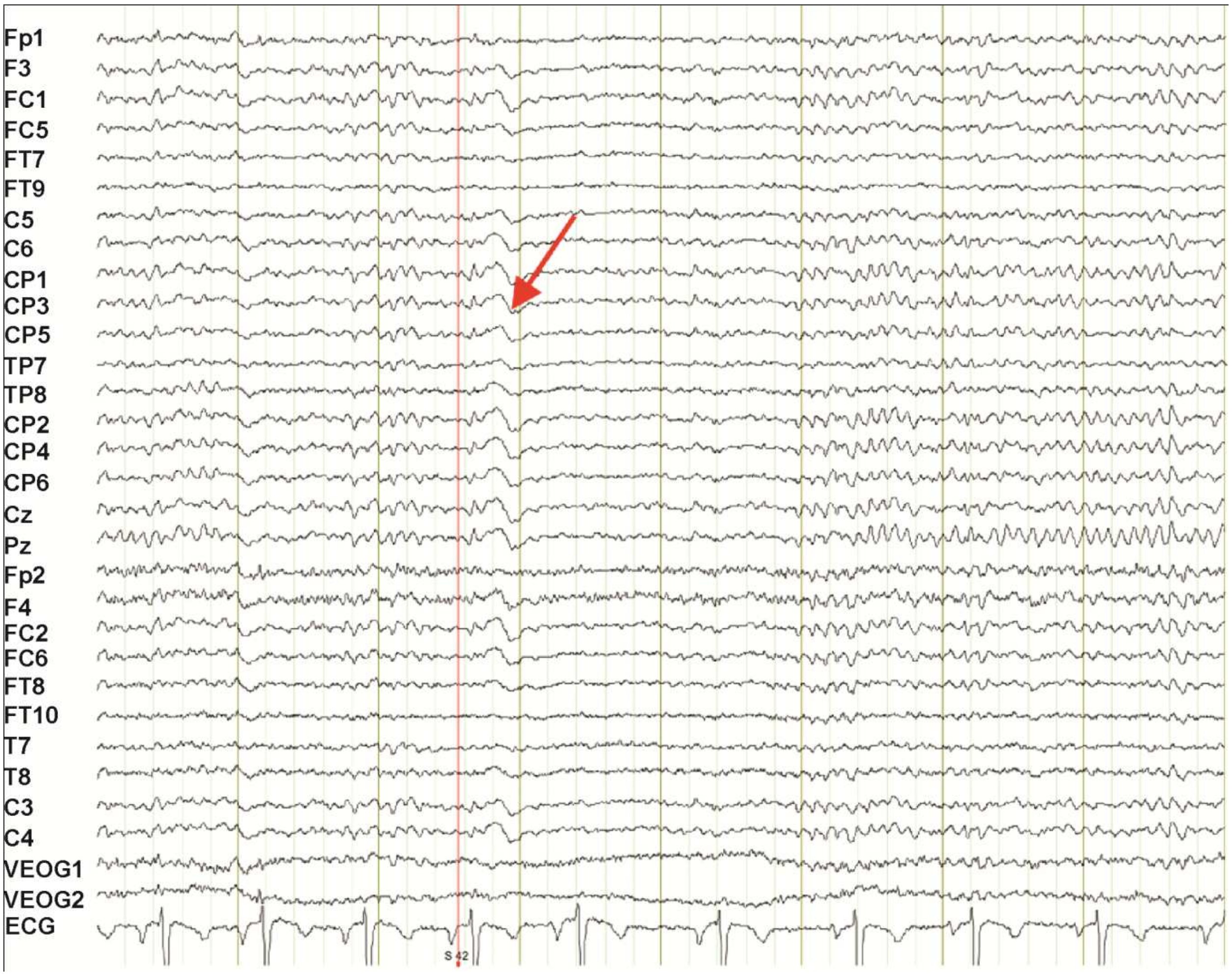

Figure 4. Specimen of an EEG recording, the recordings of EOG and of electrocardiogram with presentation of an auditory stimulus marked by the red dot and red line. The thin green lines indicate time intervals of 1 second. Note the desynchronization in the EEG beginning from the arrow for the next 1-2 seconds together with a longer lasting decrease in momentarily heart frequency.

According to widely accepted procedures [20-22], we analyzed the maximal amplitudes and latencies of the first negative component (N1), of the second positive component (P2), and we analyzed the area under the curve for the second negative component (N2) in the time range from 250-340 ms. The latter was done since not in all cases we could discern a typical or even a single peak for the component of the AEP. The MMN was measured as the difference curve between the AEP to deviant and parent chords in that time interval (Figure 5). Amplitudes and latencies were compared between parent and deviant stimuli by t-tests (student) and between the groups by one-way ANOVA as well. Separate tests were performed to determine whether the MMN-amplitudes differed for non-musicians and professional musicians as well as for normal hearing musicians and hearing-impaired musicians.

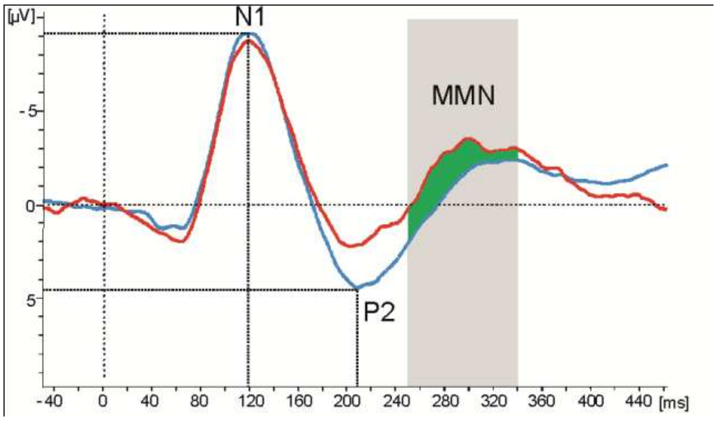

Figure 5. Specimen of a mean auditory evoked potential with labeling of the N1 and P2 components (amplitudes and latencies accentuated with dotted lines). The time interval in which we looked for the MMN is marked in grey, and the MMN is marked in green. The blue curve depicts the mean value to the frequently presented (parent) stimuli, the red one to the infrequently presented (deviant) stimuli.

To assess whether listening to mistuned chords had influence on momentary EEG-activity, we performed a Fast Fourier-Transformation (FFT) with the BrainVision Analyzer 2 in the interstimulus interval to see whether EEG-activity shifted to higher frequencies after mistuned chords. In addition, we analyzed the changes in mean heart rate (average of the heart rate during listening to in-tune music vs. mistuned tones) within the same time interval. A statistical comparison was made by means of the Wilcoxon matched pairs signed-ranks test. Statistical significance was set at 5%. Though we performed the analysis for all EEG electrodes, for better clarity we present here only data from the Cz electrodes.

3. Results

3.1. Amplitudes and latencies of N1 and P2 components of the AEP in normal hearing probands

As can be seen in Figure 6, our presented chords evoked stable and replicable AEP both in non-musicians and in professional musicians that differed only slightly between both groups.

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In both groups the presentation of mistuned chords induced larger P2 components than the presentation of normal chords.

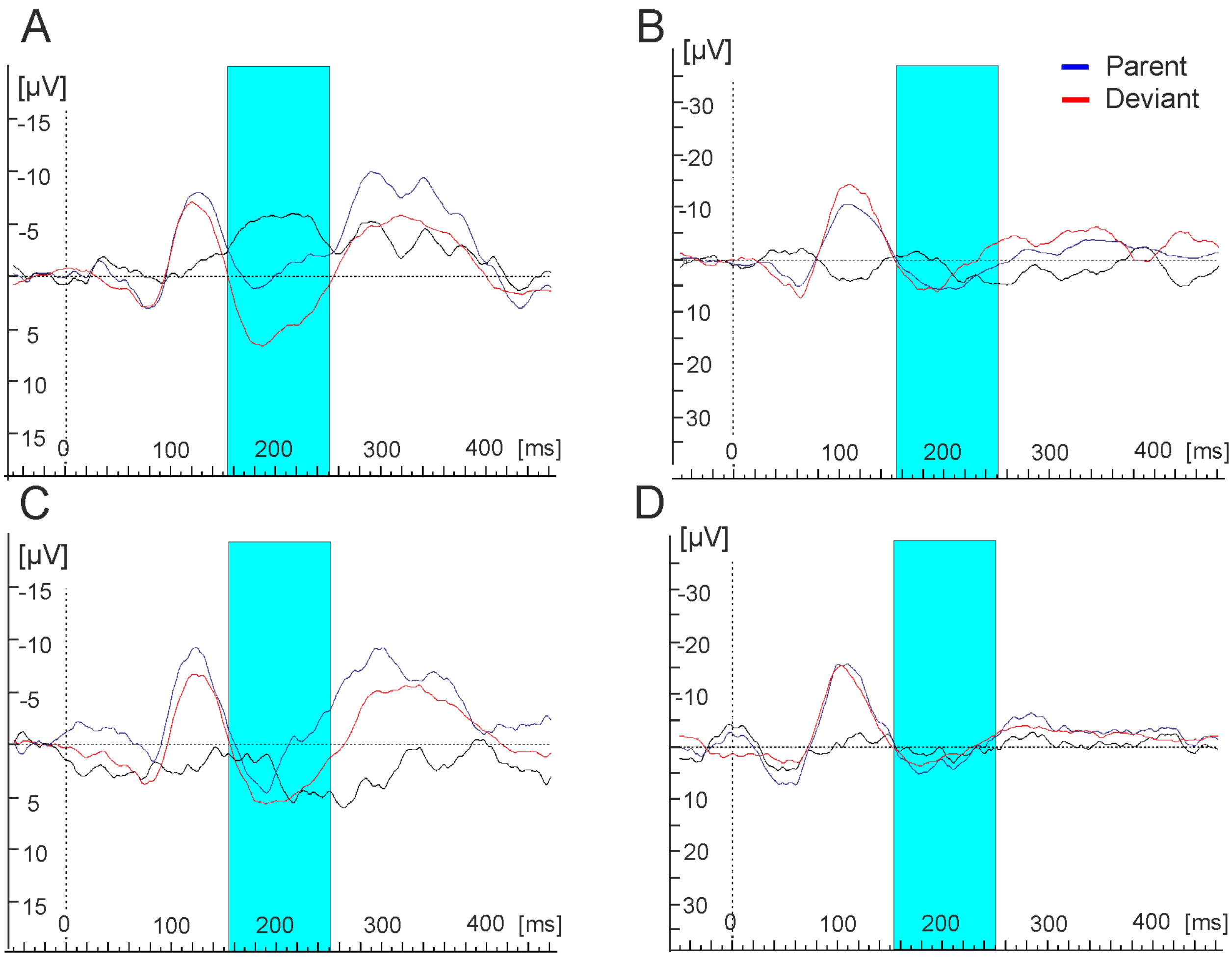

Figure 6. Mean values of AEP evoked by normal or mistuned stimuli in musicians (left diagrams) and in non-musicians (right diagrams). The bluish areas mark the time range in which we analyzed the differences between the AEP. The difference curves are shown in black. The blue lines represent AEP to frequently presented chords, the red lines AEP to the infrequently presented ones. For a better visibility the standard deviations of the curves are omitted. A and B show that normal chords occurred frequently (paradigm 1). C and D show that mistuned chords occurred frequently (paradigm 2). Note the small differences between normal tuned and mistuned chords in non-musicians in diagrams B and D.

The peak of the N1 component was seen at about 128 ms after the stimulus, the peak of the P2 component at about 224 ms after the stimulus. Mean N1 amplitudes amounted to about 7 μV, mean P2 amplitudes to 5 μV. A detailed comparison between the groups of musicians and non-musicians and the three paradigms is given in Figure 7. It should be noted that both C3-major chords resulted in markedly larger areas under the curve both for the N1 and for the P2 components in non-musicians and in musicians. However, the area under the curve of the P2 component was larger when C3-major chords were presented than when C1-major chords were presented.

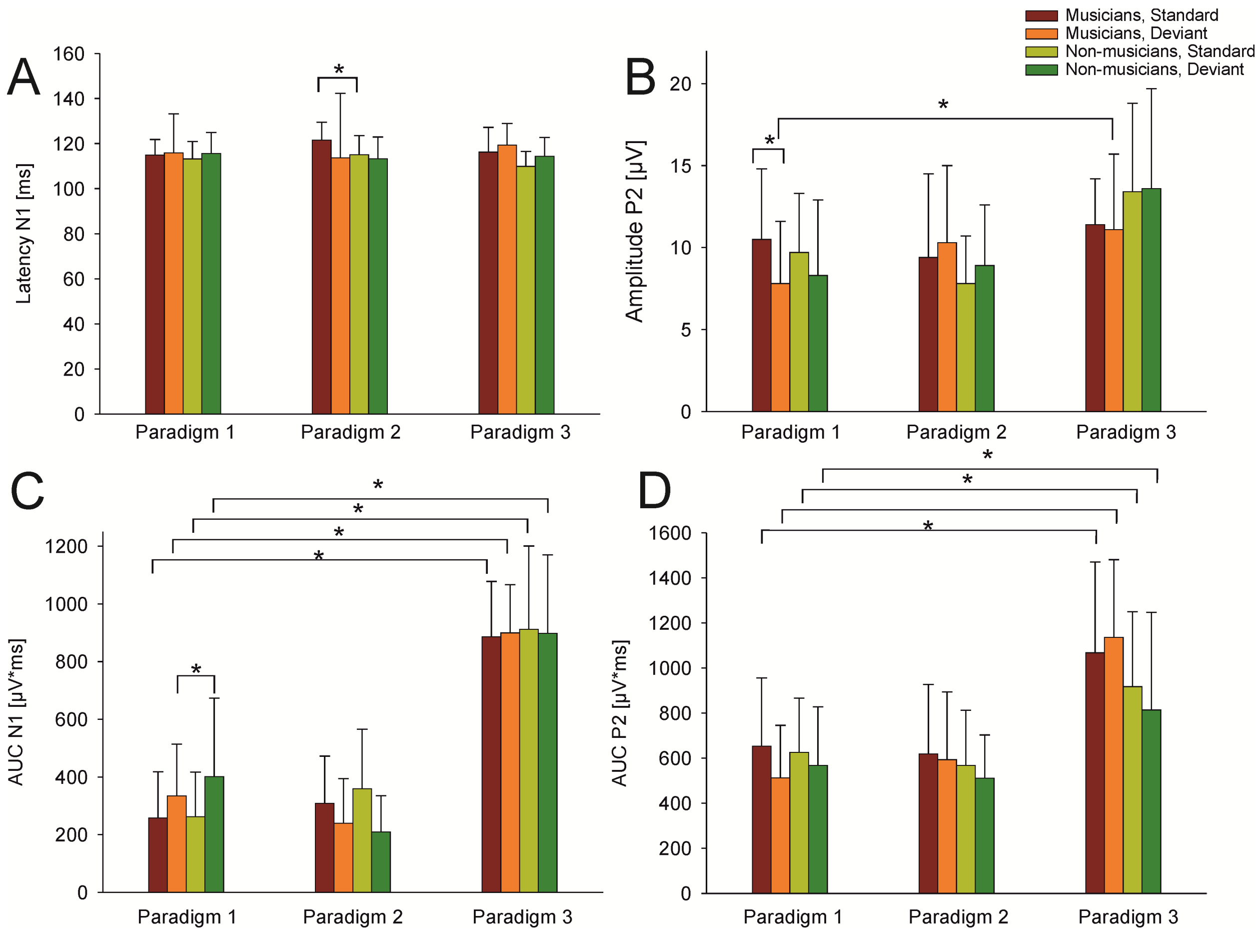

Figure 7. AEP components from normal hearing non-musicians and musicians. The bars give the mean values ± std. dev. The asterisks mark statistically significant differences ($p<0.05$). A) Latency times of the N1 component. B) Amplitudes of the P2 component. C) Areas under the curves of the N1 component. D) Areas under the curve of the P2 component.

Interestingly, the EEG activity differed markedly between both groups when the late components of the AEP were compared that were recorded from the Cz electrode and an activity map was computed by the brain vision software. Though the general pattern was alike, a general higher activity rate was seen in musicians over the temporo-occipital cortex and a lower activity in the vertex area of the brain (Figure 8).

3.2. Amplitudes and latencies of N1 and P2 components of the AEP in hearing-impaired probands

All professional musicians in this group had a hearing loss in the mid- and/or high-frequency range with a mean PTS up to 35 dB SPL. No significant differences were obtained when left and right ears were tested so a preferential side of hearing loss could be excluded. All hearing-impaired industrial workers suffered from hearing loss that was recognized as an occupational disease. The hearing deficit had a similar magnitude as in the hearing-impaired professional musicians and was also found at both ears with a slight but insignificant preference to the left ears (Figure 9).

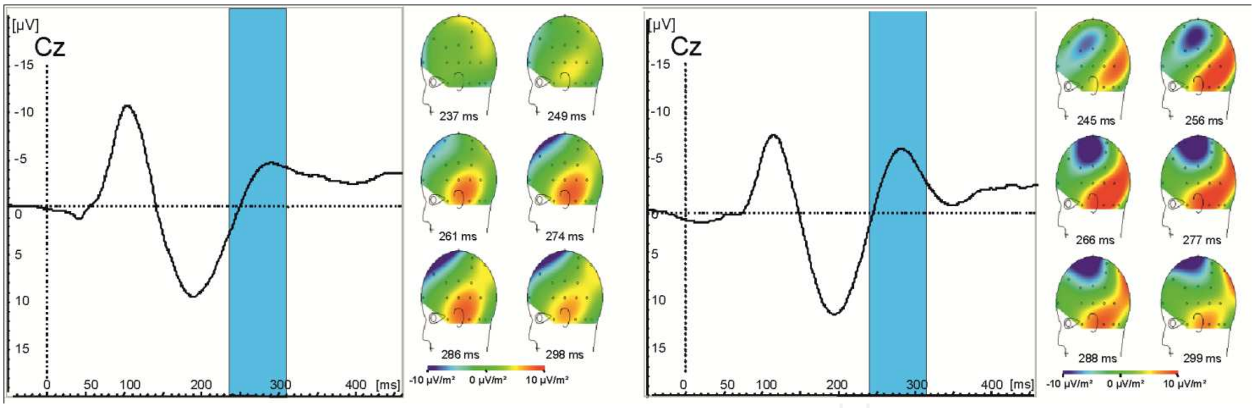

Figure 8. Comparison of cortical EEG activity after stimulation with normal C1-major chords. The AEP curves show the grand mean value from all participants and the activity maps the distribution of cortical activity at different moments after the stimulus in the time range marked in blue. A) Data from normal hearing non-musicians. B) Data from normal hearing musicians.

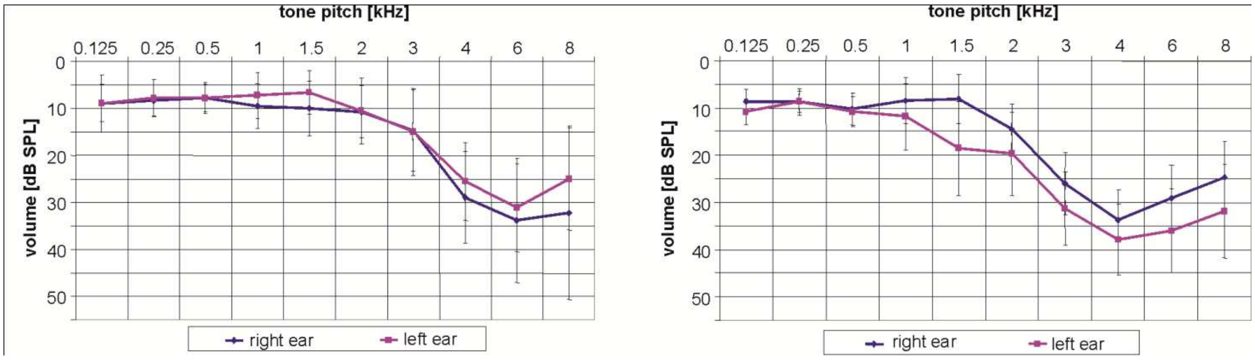

Figure 9. Mean values ± std. dev. of hearing loss in the left and right ears of the 10 hearing-impaired professional musicians (left) and of the 20 hearing-impaired industrial workers (right).

When tested with the auditory stimuli, the parameters of the AEP components differed from the data obtained in normal hearing musicians. The N1 peaks were found earlier (C1 chord 121 ms, C3 chord 109 ms after stimulus) and had larger amplitudes (C1 chord 11 μV, C3 chord 11 μV). The same was seen for the P2 peaks (latency for C1 chords 213 ms, for C3 chords 202 ms; amplitude for C1 chords 5 μV, for C3 chords 8 μV). The latter difference was even significant between C1 chords and C3 chords in this group.

For both stimulus types (normal or mistuned), neither amplitudes nor latencies of the N1 component showed significant differences between non-musicians, normal hearing or hearing-impaired musicians. Responses to parent or deviant stimuli did not differ, regardless whether in-tune or mistuned chords were given as parent stimuli. Similarly, no significant difference existed when comparing the N1 components to the mid-frequency (C1; paradigm 1) or to high-frequency (C3; paradigm 3) stimulation when the chords were mistuned by either 50 cent or by 12 cent.

The workers were first presented the same auditory stimuli as the other participants in this study, i.e., C1-major chords. When analyzing the AEP, we found later N1 amplitudes (peak

134 ms after stimulus) when the paradigm 1 was used, and same latencies as in non-musicians, when the paradigm 2 was used (N1 peak 128 ms after stimulus). The N1 amplitudes ranged from 10 to 12 μV and differed only slightly from those we obtained in non-musicians (Figure 10A and 10B). A similar result was seen when we analyzed the P2 components of the AEP. In this group, the latencies ranged from 228 to 237 ms after stimulus in paradigm 1 and from 218 to 226 ms in paradigm 2 that was later than in musicians, but in the same range as in non-musicians. The P2 amplitudes ranged from 7 to 11 μV and did not differ significantly to the other participants. Both musicians and industrial workers had larger P2 areas under the curve either when the mistuned stimuli were presented rarely in the paradigms 1 (Figure 10C) or often in the paradigms 2 (Figure 10D).

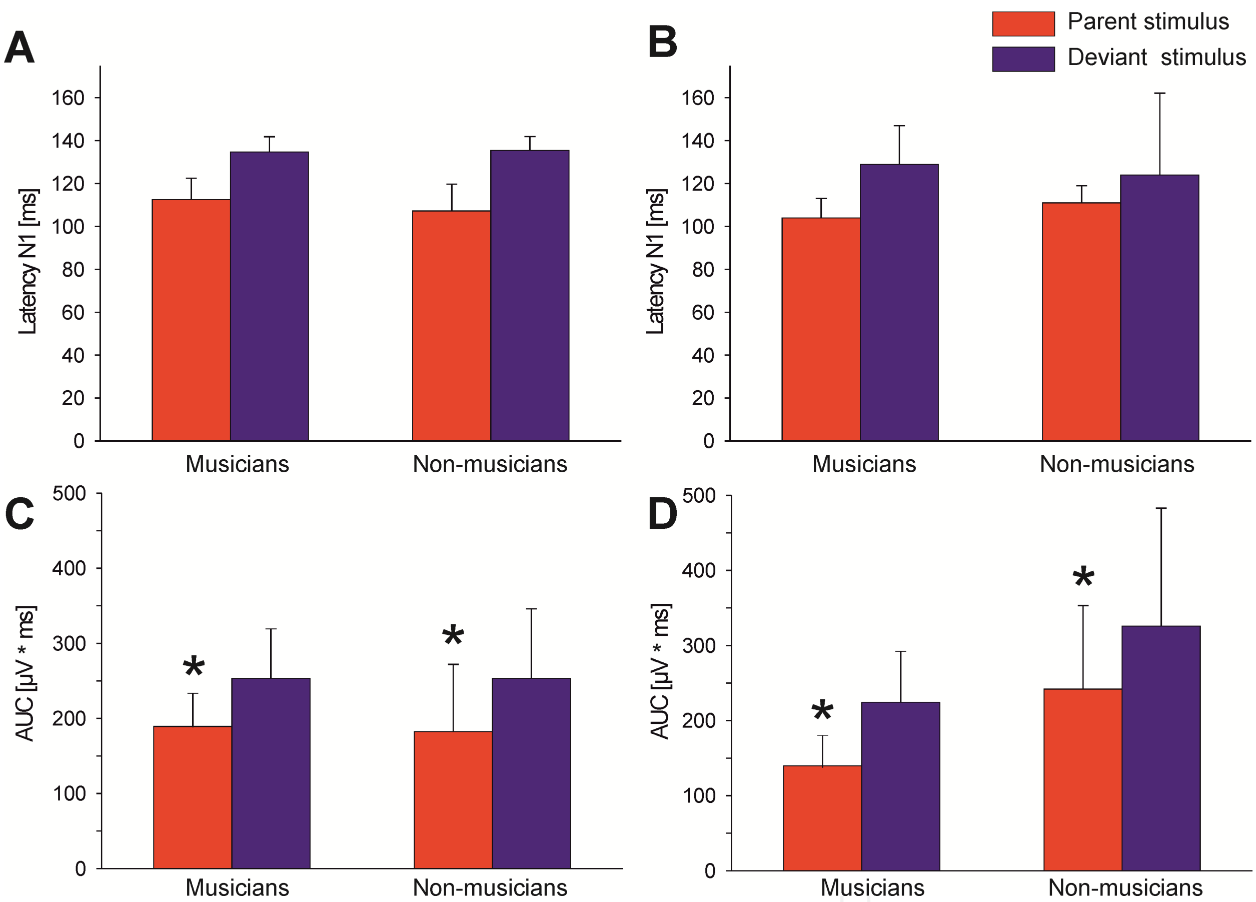

Figure 10. Comparison of amplitudes of the N1 components and of the areas under the curve for the P2 components of the AEP in hearing-impaired musicians and in hearing-impaired industrial workers. Data are presented as mean values ± std. dev. The asterisk marks statistically significant differences ($p<0.05$). A) N1 latencies in paradigm 1. B) N1 latencies in paradigm 2. C) P2 areas under the curve in paradigm 1. D) P2 areas under the curve in paradigm 2.

In a second part of the study, the workers had to listen to machine noise that was either unchanged (parent stimulus) or interrupted/disturbed by short high-pitched whistles. This type of stimulation did not evoke typical AEP, but was used to look for activity changes in the EEG (see below).

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3.3. Comparison of the MMN

When interviewed after the series both normal hearing and hearing-impaired musicians complained about the mistuned chords. They told us that they were annoyed at the mistuned chords, but hearing-impaired non-musicians and hearing-impaired industrial workers had not perceived the small differences between the stimuli.

Hearing-impaired musicians were still able to distinguish between in-tune and mistuned chords in both the C1 and in the C3 chords regardless of the degree of mistuning. Their areas under the curve for the MMN were significantly larger when the C1 chords were presented and mistuned stimuli occurred rarely (paradigm 1), which is shown in Figure 11.

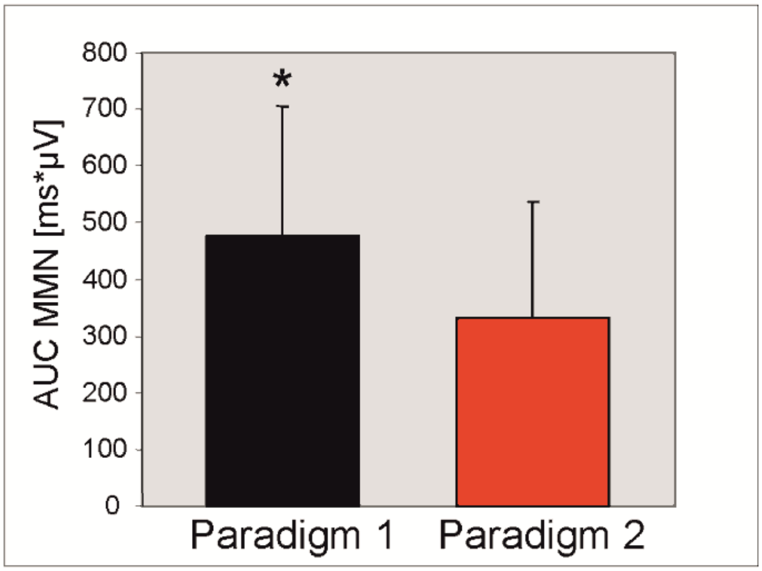

Figure 11. Comparison of areas under the curve for the stimulation with C1 chords in paradigm 1 (black bar) and in paradigm 2 (red bar). Data are presented as mean values ± std. dev. The asterisk marks a significant difference ($p<0.05$).

Independent from hearing impairment, rarely occurring chords (either normal or mistuned) in the musicians group evoked larger areas under the curve for the P2 components (Figure 12).

Interestingly, in hearing-impaired industrial workers, a similar but statistically insignificant difference was seen between the areas under the curve for the P2 component, though the workers told in the interview that they did not observe any differences between the presented chords. This difference was seen both when the mistuned stimulus was presented rarely or often (Figure 13).

The investigation of the MMN curves (AEP to deviant minus AEP to standard stimuli) confirmed differences between non-musicians and both groups of musicians. In normal hearing musicians, the MMN was found in the time range from 180-250 ms after stimulus and a similar, but even longer lasting MMN (up to 300 ms after stimulus), was seen in hearing-impaired musicians. The MMN curves after high-frequency stimulation (C3 chords), however, allowed a clear differentiation between professional musicians and non-musicians. Non-

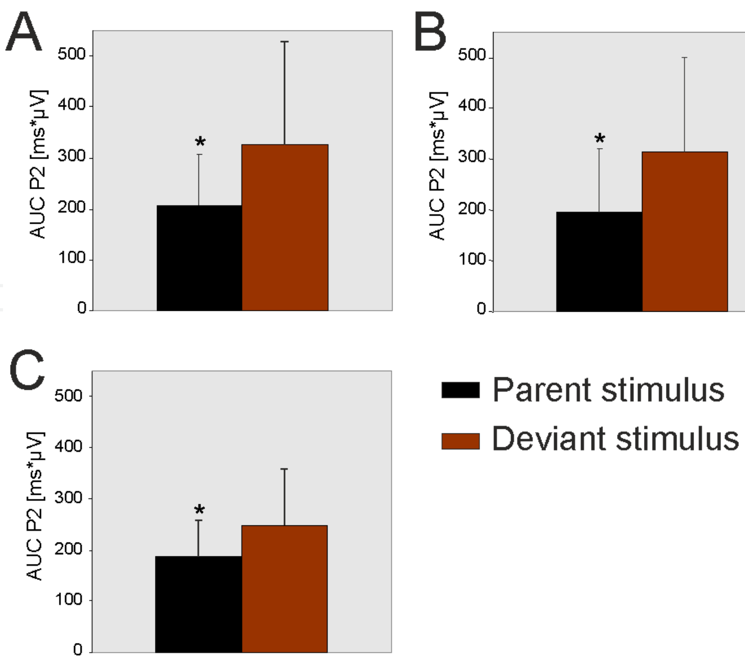

Figure 12. Comparison of the areas under the curve for the P2 components of the AEP in hearing-impaired professional musicians. Data are presented as mean values ± std. dev. The asterisks mark significant differences (p<0.05). Black bars show responses to the parent stimuli, the brown bars show the responses to the deviant stimuli. A) C1 chord, paradigm 1. B) C1chord, paradigm 2. C) C3 chord, paradigm 3.

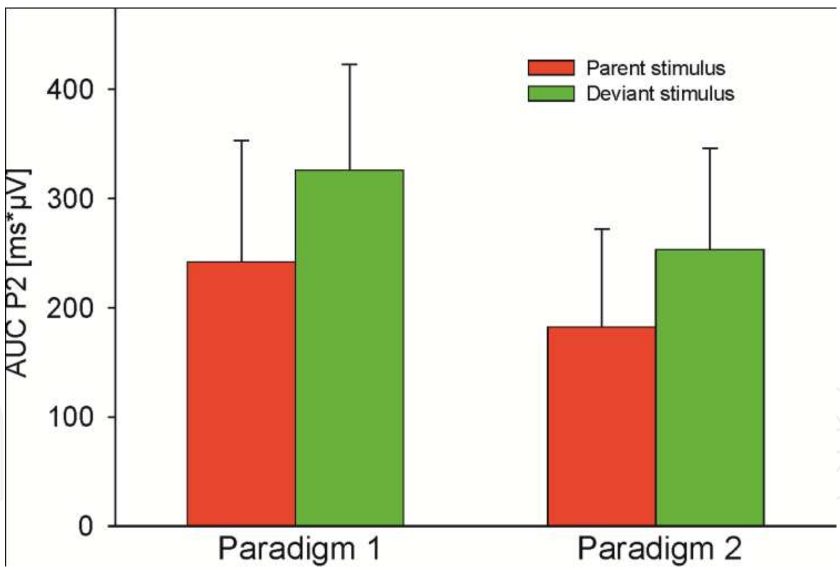

Figure 13. Areas under the curve for the P2 component recorded in hearing-impaired workers. Data are presented as mean values ± std. dev. The red bars show responses to parent stimuli, the green ones to deviant stimuli. A) Presentation in paradigm 1 (mistuned stimuli occur rarely). B) Presentation in paradigm 2 (normal stimuli occur rarely).

musicians had no typical MMN in the observed time range. In normal hearing musicians, this MMN occurred in the range of 250-340 ms after stimulus and a small, but clearly discernable MMN was also found in hearing-impaired musicians. In the latter group, however, the MMN started earlier (220-230 ms after stimulus).

3.4. FFT analysis of the EEG and heart rate analysis

Due to the instructions to the participants (closed eyes, relaxed sitting position, no directed attention to the stimuli), highest spectral power was found in the alpha band, thus confirming that the participants followed the instructions. In both groups of musicians, we found a shift in power density towards higher alpha EEG activity in the interstimulus intervals after presentation of mistuned chords. Such a large shift failed to occur in non-musicians, when the same stimuli were presented. In this group EEG power spectra density was the same, regardless whether in-tune or mistuned chords were presented (Figure 14).

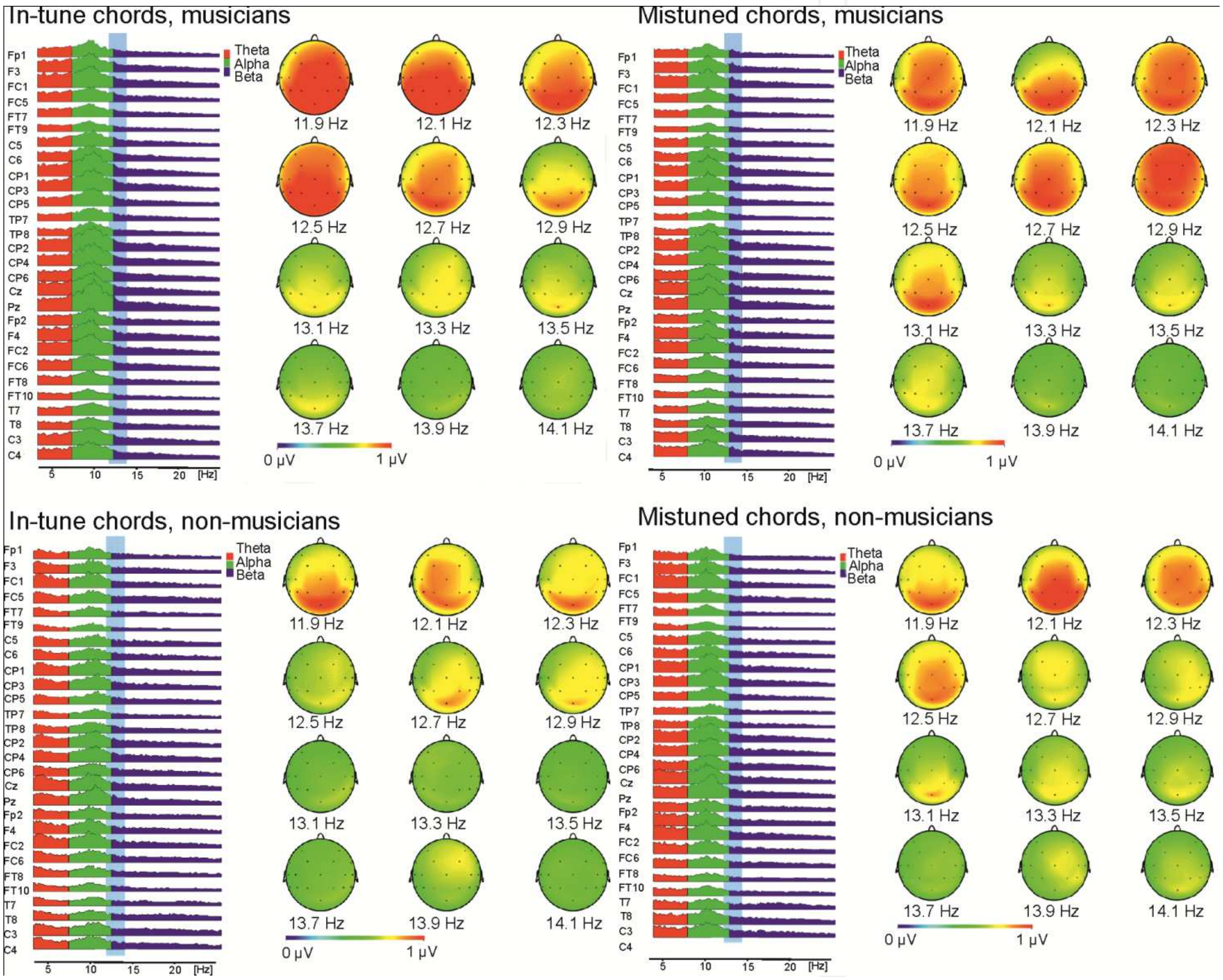

Figure 14. FFT-analysis of the EEG shown as diagrams of regional spectral EEG power and as frequency split maps for musicians (top) and non-musicians (bottom). The light blue bar in the power spectra marks the frequency range that is further analyzed in the frequency split maps. Note the activity shifts towards higher alpha frequencies in musicians when mistuned stimuli were presented. Such a shift failed to occur in non-musicians.

In the same groups we analyzed the heart rates and found a significant increase in mean heart rate in musicians after listening to mistuned chords compared to the resting situation, but no significant differences when comparing resting situation vs. hearing of in-tune chords (resting situation 69.6±12.4 beats per minute, 70.2±12.4 beats per minute after in-tune chords, 71.4±11.5

beats per minute after mistuned chords; n=15; Wilcoxon matched pairs signed-ranks test, p=0.0353). The mean heart frequency, however, did not change in non-musicians (resting situation 60,7±8.1 beats per minute, 60.5±7.5 beats per minute after in-tune chords, 60.8±8.7 beats per minute after mistuned chords; n=10).

Hearing-impaired industrial workers always negated to have noticed the mistuned stimuli, though we had recorded typical MMN to the rare stimulus. In order to present a profession-specific sound to this group, we had used short sequences of the unchanged machine noise and the same noise with high-pitched whistles that sounded like very short pips.

As expected from the pre-trial interviews where the hearing-impaired workers claimed that they easily could discern even one broken bottle in the machine sound, the workers confirmed after the trials that they had heard the rarely occurring disturbed noise samples. In the EEG, the occurrence of these rare stimuli caused a desynchronization lasting for 5-6 seconds (Figure 15).

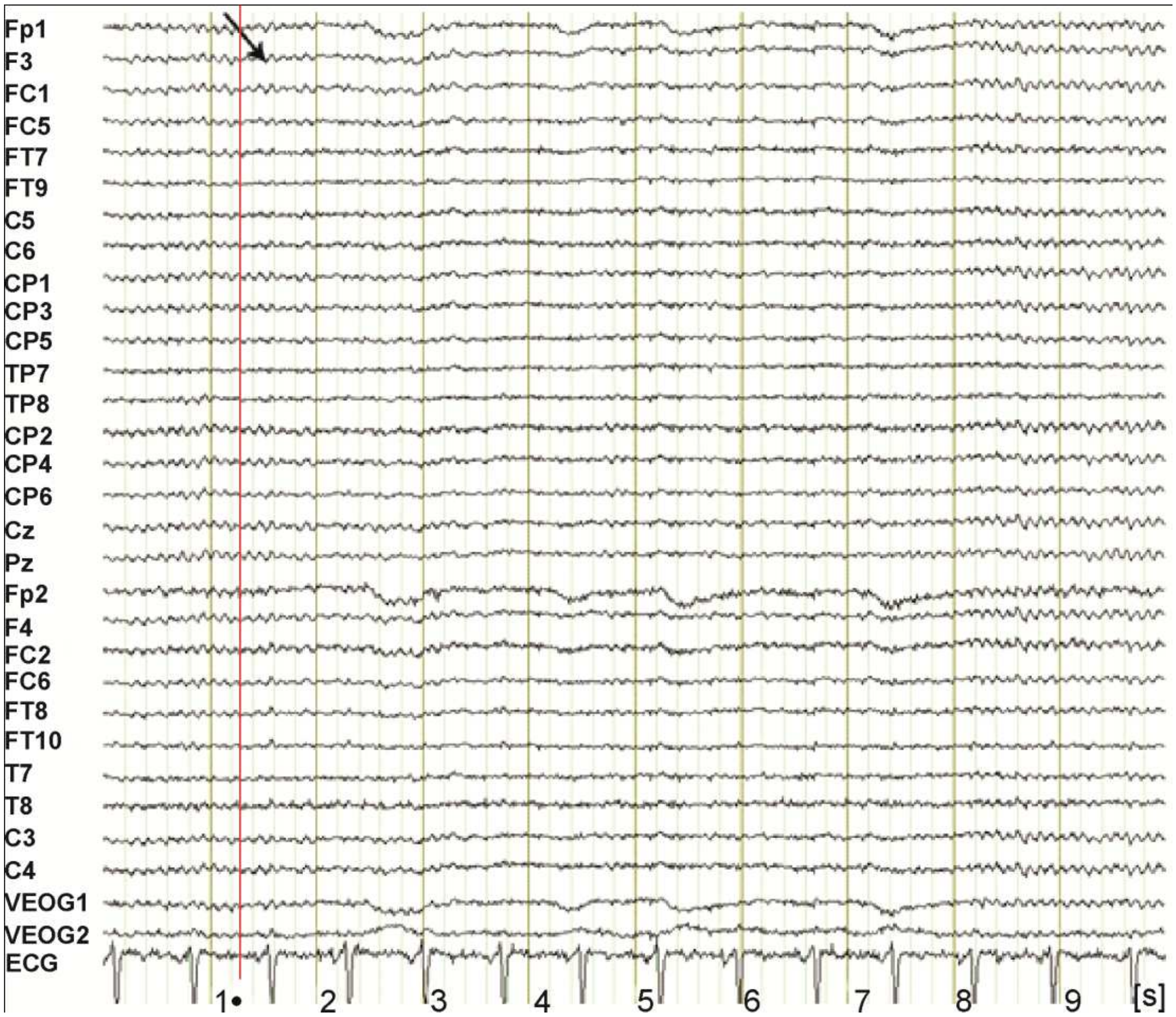

Figure 15. Sample EEG recording from one hearing-impaired industrial worker. The black dot at the bottom marks the presentation of the disturbed machine noise; the onset of the desynchronization in the EEG is marked by an arrow.

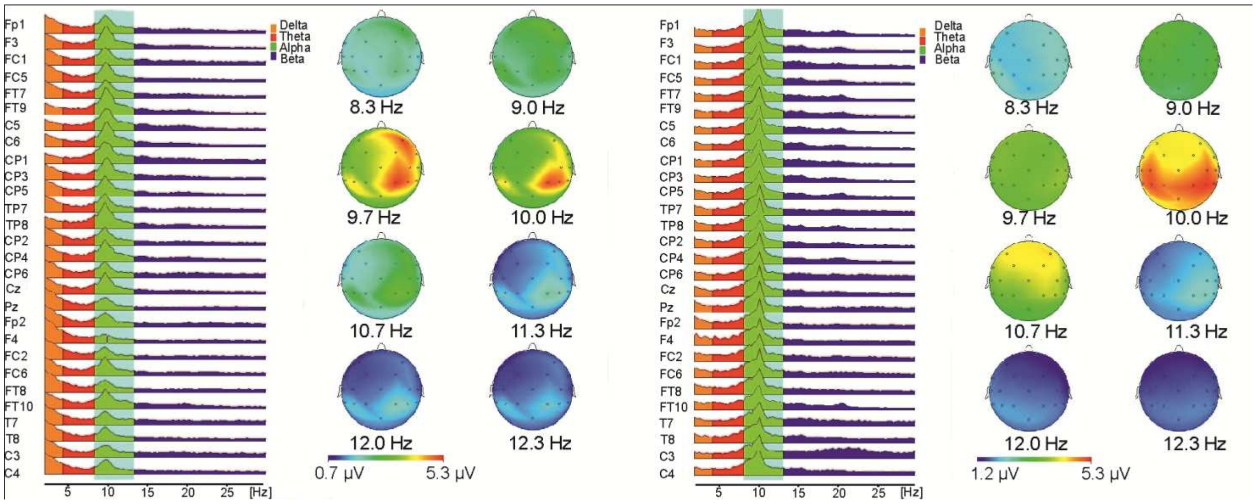

Figure 16. FFT-analysis of the EEG shown as diagrams of regional spectral EEG power and as frequency split maps for normal undisturbed machine noise was presented (left panel), and when the machine noise was disturbed by short pips (right panel). The light blue bar in the power spectra marks the frequency range that is further analyzed in the frequency split maps.

We performed the same FFT-analysis of the EEG in the workers and revealed a shift in the frequency towards higher alpha bands when the disturbed noise was presented (Figure 16). During undisturbed noise the EEG activity had its maximum at 9.7 Hz and was preferentially distributed in the right hemisphere, and only a small area of this hemisphere showed a 10.0 Hz EEG. When we presented the disturbed noise, in a larger area of the brain at both hemispheres a 10.0 Hz EEG and in the frontal parts of the cortex even a 10.7 Hz EEG were observed. The mean EEG frequency increased from 9.2±0.6 Hz during undisturbed noise to 9.4±0.6 Hz during disturbed noise.

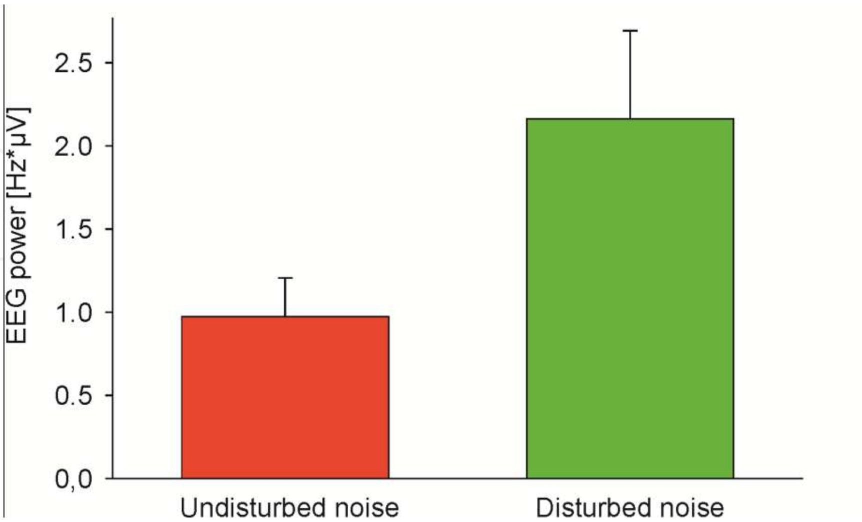

Figure 17. Mean values of EEG power spectra ± std. dev. in hearing-impaired industrial workers when typical machine noise was presented. The red bar shows the data during undisturbed noise; the green one shows the data during disturbed noise.

In addition, we analyzed the power spectra in the frequency range from 12 to 14 Hz at the Cz electrode and found significantly higher regional EEG spectral power in hearing-impaired industrial workers when disturbed machine noise was presented (Figure 17).

4. Discussion

For the first time in this study, profession-specific stimuli were used to assess the effects of hearing deficits in professional musicians and in industrial workers. Here we have shown that parameters of AEP and MMN to mistuned chords differ between musicians and non-musicians, as well as between normal hearing and hearing-impaired musicians, and that components of the AEP and the MMN can be used to differentiate between the three investigated groups. FFT analysis of the EEG in the interstimulus intervals confirmed that mistuned chords caused a state of higher EEG activity only in musicians, regardless of their hearing loss. Another evidence was the occurrence of heart rate changes only in musicians. Therefore we conclude that both perception and processing of musical signals differ between musicians and non-musicians. In hearing-impaired workers, the disturbed machine noise caused a state of higher EEG activity as well.

It is known that complex stimuli such as complex derived words can produce MMN [23]. The stimuli we used were chosen from the typical occupational environment of the professional musician, i.e., musical chords. Complex musical sounds are used to produce MMN, e.g., to compare timbre processing in harmonically rich sounds versus single sinusoidal tones [24]. We had expected that musicians with ongoing musical training over several years have learned to hear and to evaluate these stimuli with their professional memory. Marked differences between tuned and mistuned chords should be recognized easily by musicians, but also by non-musicians. Smaller differences, however, when stimuli were presented in the high-frequency range should be recognized only by musicians. To our knowledge, such a study had not been done before in hearing-impaired musicians.

Intense musical training resulted in an increase in area of primary and secondary auditory cortices [25-27]. In line with this finding, fMRI investigations in musicians revealed a co-activation of both auditory and sensomotor areas in the cortex, thus showing that musical training changes the connectivity and probably also the processing strategies in the brain of musicians [28-30]. Long-term musical training enhances the short-term memory for auditory stimuli and eased behavioral tasks, e.g., detection of deviant tones in a series of auditory stimuli [31].

Our results confirmed the efficacy of comparison of event-related potentials to differentiate between trained musicians and non-musicians [32,33]. The effect of training to induce neural plasticity in the auditory system has been shown in musical conductors compared to non-musicians in a spatial detection task [34], in a pitch detection task [35] or in MMN evoked by variations of complex tone patterns, where long-term musical training modulated the encoding of wrong tones in the right hemisphere of musicians [36]. This is an ongoing process starting in pre-adolescence, since musically trained children had larger MMN to slightly mistuned tones compared to age-matched, non-trained children already at the age of 11, thus confirming that musical training indeed could be responsible for the larger negativity [37]. The cortical plasticity can even be improved, if not only auditory but also somatosensory tasks should be solved, e.g., learning to judge whether music was correctly played versus learning to play an instrument [38]. Interestingly, in hearing-impaired musicians we found clearly distinguishable MMNs, as well as changes in EEG power spectra after presentation of mistuned chords. Even when the stimulus was in the frequency range that was affected by the hearing disability (C3 paradigm), the professional musicians were able to differentiate between in-tune and mistuned chords. However, the normal hearing untrained non-musicians were only able to differentiate to heavily mistuned (50 cent) stimuli, but the hearing impaired did not. The results of interviews confirmed that the mistuned stimuli were recognized both by normal hearing and by hearing-impaired musicians and caused a state of unhappiness.

We could prove this when we tested the hearing-impaired workers with chord stimuli. The workers had similar hearing deficits in a similar frequency range as the hearing professional musicians. The musicians easily recognized the mistuned stimuli and commented on their occurrence in the interviews after the trials, but the workers who never before had heard those stimuli did not. The early AEP components (N1 amplitudes and latencies) did not indicate different processing of the mistuned chords by the workers. The late AEP components (P2 area under the curve and MMN), however, indicated that the mistuned stimuli were sensed and processed differently, even if the person was not aware of this stimulus [39]. Unfortunately, we could not test this phenomenon reversely with the professional musicians, since they refused stimulation with machine noise. We suppose that such unfamiliar stimuli would be difficult to discern by the musicians.

To explain the ability of hearing-impaired musicians to differentiate between "right" and "wrong" tunes several considerations are necessary. We can exclude a significantly varied loudness of the tuned versus the mistuned stimuli. In the group of hearing-impaired musicians, audiological investigations provided evidence for a diminished peripheral input. This impairment might explain the delayed and smaller amplitude of the P2 component as well as the smaller areas under the curve for the N2 component and the smaller resulting MMNs than in normal hearing musicians. Interestingly, the AEP had a similar amplitude and time shape both after stimulation with the high-frequent C3 paradigm and with the mid-frequent C1-major chords, thus confirming that the hearing damage should have affected a larger part of the cochlea. In agreement with a previous study [8], we had instructed the participants to sit relaxed and not to pay attention to the chords. Therefore, we conclude that we were able to record a non-attentional, automatic processing of musical signals. Musicians that were trained to those signals should process this information more effectively [8]. In line with this, musicians were less dependent on the salience of an acoustical environment, but in non-musicians salience had a stronger impact on the processing of complex tone patterns [36]. Assuming that musical training had already caused this effect before hearing impairment started, it is likely that the diminished input could be processed in professional musicians with still higher efficacy than in untrained non-musicians. Another statement in the literature [10] gives support to our interpretation: musical training should result in a more accurate tuning of the frequency-specific neurons in musicians compared to non-musicians. There is indication for a better top-down modulation of auditory processing in trained musicians for both musical sounds and speech [40]. We suppose, therefore, that a better tuning function of the neurons would result in more accurate processing of the rest of a signal when the input is diminished by cochlear damage. In line with this, we found in hearing-impaired musicians significant earlier N1 and P2 components than in hearing-impaired industrial workers when musician-specific chords were used as stimuli.

We conclude that our observed smaller MMNs to mistuned chords in hearing-impaired professional musicians reflect central compensation mechanisms that are able to improve the processing of profession-specific signals, i.e., musical chords. This compensation does not take place in situations of normal life (i.e., without ongoing formal training), e.g., watching TV, using a headphone or cellular phone, or in situations with a loud background that disturbs the incoming signals. In these situations, hearing-impaired musicians complain about the hearing deficit though they are able to play their instruments correctly.

The musicians investigated in our study were interested in learning about hearing damage and the proper use of hearing protectors. Nevertheless, the acceptance of hearing protectors (custom-built ear plugs for specific instruments) among musicians in classical orchestras is very small; more than 90% dislike such devices. Another number has been observed among rock musicians - there is a rate of nearly 50% who accept such hearing protectors [41,42]. Hearing loss among professional musicians in Germany has so far not been accepted as an occupational disease though sound intensities exceed the limits allowed for a working shift in many orchestras [12,43]. The lack of rules to prevent hearing loss in professional classical musicians and the ongoing dispute whether sound exposure during rehearsals or performances is high enough to induce hearing loss hinders the discussion to foster the use of hearing protection in that profession [44-48].

In conclusion, our data indicate that a differentiation between non-musicians and musicians is possible by analyzing AEP components or the MMN when profession-specific stimuli are used. The MMN was still present in hearing-impaired professional musicians, although they had a hearing deficit in the frequency range of the musical stimuli. Probably, the intense musical training has enhanced the processing structures and/or efficacy to evaluate the musical stimulus. A similar result was seen in the workers: ongoing professional training enabled the detection of disturbed machine noise though this group was unable to detect differences in non-trained musical sounds.

To answer the hypotheses postulated at the beginning:

1. Musical chords are a suitable stimulus to evoke stable and replicable AEP both in musicians and in people who are not trained to musical stimuli. AEP evoked by those stimuli can be used to differentiate between trained and untrained persons. Especially the late components of the AEP differ and depend on the learned stimulus. Ongoing professional training to specific sounds is a learning process that is reflected in different sound processing and in the late components of the AEP.

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2. After ongoing training to profession-specific sounds, a person is able to notice even small differences of a stimulus, even though the stimulus is presented in a frequency range with impaired hearing function. This phenomenon should be noted when hearing thresholds are measured. A PTS does not always represent an inability to perform a specific (learned) hearing task.

3. The occurrence of differences in the stimuli that is reflected in different parameters of the AEP does not imply an awareness of perception of the stimulus. This is important when foreign stimuli are used and the proband is asked for recognition of different stimuli.

Nomenclature and Abbreviations

AEP; Auditory evoked potential

ANOVA; Analysis of variance

DPOAE; Distortion product otoacoustic emissions

EEG; Electroencephalogram

FFT; Fast Fourier transformation

MMN; Mismatch Negativity

PTS; Permanent threshold shift

TEOAE; Transient-evoked otoacoustic emissions

VEOG; Vertical electrooculogram

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