

## Mismatch negativity to acoustical illusion of beat: How and where the change detection takes place?



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### ABSTRACT

In case of binaural presentation of two tones with slightly different frequencies the structures of brainstem can no longer follow the interaural time differences (ITD) resulting in an illusory perception of beat corresponding to frequency difference between the two prime tones. Hence, the beat-frequency does not exist in the prime tones presented to either ear. This study used binaural beats to explore the nature of acoustic deviance detection in humans by means of magnetoencephalography (MEG). Recent research suggests that the auditory change detection is a multistage process. To test this, we employed 26 Hz-binaural beats in a classical oddball paradigm. However, the prime tones (250 Hz and 276 Hz) were switched between the ears in the case of the deviant-beat. Consequently, when the deviant is presented, the cochleae and auditory nerves receive a “new afferent”, although the standards and the deviants are heard identical (26 Hz-beats). This allowed us to explore the contribution of auditory periphery to change detection process, and furthermore, to evaluate its influence on beats-related auditory steady-state responses (ASSRs). LORETA-source current density estimates of the evoked fields in a typical mismatch negativity time-window (MMN) and the subsequent difference-ASSRs were determined and compared. The results revealed an MMN generated by a complex neural network including the right parietal lobe and the left middle frontal gyrus. Furthermore, difference-ASSR was generated in the paracentral gyrus. Additionally, psychophysical measures showed no perceptual difference between the standard- and deviant-beats when isolated by noise. These results suggest that the auditory periphery has an important contribution to novelty detection already at sub-cortical level. Overall, the present findings support the notion of hierarchically organized acoustic novelty detection system.

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### Introduction

The detection of unexpected changes in a regular acoustic pattern is essential for survival. The mismatch negativity component (MMN) of the event-related activity (Näätänen et al., 1978) is a useful research tool reflecting the brain's automatic ability to detect acoustic violations in a repetitive sequence of sounds (for review see (Näätänen and Escera, 2000)). Typically, the MMN is obtained as a negative deflection of the event related activity, between 100 and 250 ms after stimulus onset in response to rare deviant stimuli embedded in a sequence of standard stimuli.

While the change detection in humans has traditionally been indicated by means of MMN, recent studies demonstrated the existence of deviance detection in the brainstem- and middle-latency evoked responses (with the latency between 20 and 50 ms) (Grimm and Escera, 2012; Slabu et al., 2010). Accordingly, the auditory change-detection also engages brain structures prior to cortical ones. These authors proposed that the encoding of regularities and the detection of violations is a basic principle of acoustic processing and that the MMN recorded from the human scalp includes the hierarchical representation of this activity over the different stages of the auditory system (Grimm and Escera, 2012; Slabu et al., 2010). Therefore, a related question is whether the auditory system is sensitive to these changes simply based on stimulus specific adaptation, as it has been suggested by most of the animal studies (Fishman and Steinschneider, 2012; Perez-Gonzalez et al., 2005; Ulanovsky et al., 2003; von der Behrens et al., 2009) or it relies on a higher order cortical controlling system that monitors the stimulus violations based on short-term memory representation established by the standards (Näätänen and Winkler, 1999; Näätänen et al., 2007; Picton et al., 2000). These two interpretations result in an ongoing debate of whether

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MMN originates from novel cortical generators (Näätänen et al., 2007) or it is simply a modulation of the obligatory transient response components, such as N1 that is evoked about 100 ms after the stimulus onset (May and Tiitinen, 2010).

The goal of the present study was to explore the neural bases of acoustic deviance detection throughout the different levels of the auditory system. To achieve this aim we employed magnetoencephalography (MEG) in a novel approach: in the classical oddball paradigm (Näätänen et al., 1978) binaural beats were used instead of simple tones. The “binaural beat” is an acoustic phenomenon that could be experienced in case of dichotic presentation of two different tones via headphones (Oster, 1973). It provides a classic example of binaural interaction considered to be a result of neural coupling in the brainstem structures that receive input from both ears. Superior olivary complex (SOC) is the first station of binaural interaction. Its function is to localize sounds following the changes in the arrival time between the two ears (the so called interaural time difference [ITD]) (Blauert, 1982). Below that stage, two separate pathways conduct the upcoming sensory information from the two ears. However, in case of simultaneous binaural presentation of two tones with slightly different frequencies the SOC can no longer follow the interaural temporal changes, resulting in an illusory perception of beat that corresponds to the frequency difference between the prime tones (Oster, 1973; Schwarz and Taylor, 2005).

The standards in our paradigm were, therefore, a product of binaural interaction between 250 Hz-tone played in the left ear and 276 Hz-tone played in the right ear. The deviants resulted from the same interaction; however, the two tones were simply inverted from left–right to right–left ear (right–250 Hz and left–276 Hz). Therefore, when presented in isolation (not as a sequence), the two prime tones that form the standard and the deviant result in the same perception of binaural beat and identical auditory steady-state responses (ASSRs) at 26 Hz that could be registered in humans. Hence our hypothesis was that the repetition of the standards in a sequence would cause peripheral adaptation in the left–250 Hz channel and the right–276 Hz channel in the cochlea and auditory nerves. Consequently, the deviant would produce signal deviation already on a sub-cortical level. Therefore, we anticipated that the stimulus deviation in the sub-cortical structures would cause more vigorous responses that will be transduced to cortical level and registered by the MEG, regardless of the binaural interaction in the brainstem. This would allow us to investigate whether, and to what extent, the sub-cortical adaptation contributes to the cortical novelty detection system. In other words, we attempted to determine whether the violation of the regularity that has occurred at the level of the cochlea and auditory nerves, in terms of frequency-specific adaptation and alteration, could lead to differences in the cortical evoked fields, in terms of mismatch negativity (MMN), although the original stimuli (prime tones) have fused into one unified stimulus at the level of brainstem. Moreover, the experimental design was organized as “reversed standard condition” consisting of two subsequent blocks. Thus, the “standard” beats of the first block were presented as “deviant” beats in the second block and vice versa. This allowed us to compare the deviants with the very same stimuli of the next block occurring in the context of standards and vice versa, in order to oversee for possible physical differences between the two binaural beats when the prime tones were switched between the ears.

Additionally, the present experimental design allowed us to evaluate the influence of the change detection process on the ASSRs. It has been found previously that stimuli with different modulation frequencies elicit ASSRs at the modulating rate and its harmonics (Ross et al., 2000). The “standard” and “deviant” beats used in the present experiment evoke ASSRs with one and the same frequency (26 Hz-beat). Hence, this would make possible to assign the expected difference-ASSR to acoustic deviance detection instead of different amplitude modulations.

Finally, we anticipated that our MEG results would reveal different networks of cortical areas to be involved in the processing of the different

evoked field components, namely the ASSRs and the MMN, during the change detection process.

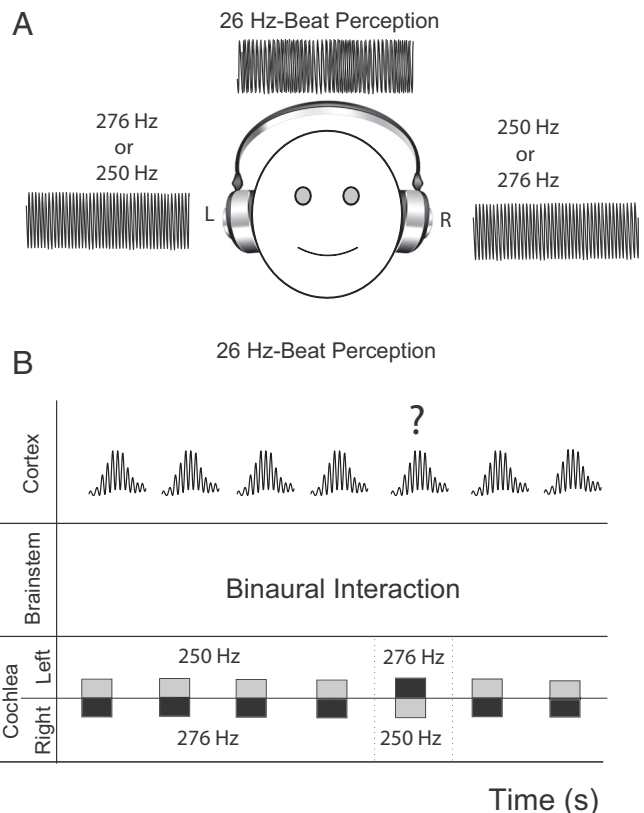
## Methods

### Participants

Fifteen right-handed subjects (7 males), aged between 20 and 30 years (26.8 years mean age), participated in this study. None of them had a history of otological or neurological disorders. A normal audiological status was verified by pure-tone audiometry in terms of air conduction hearing thresholds less than 10 dB. Pure-tone thresholds were measured for octave frequency from 250 to 4000 Hz. All participants gave written, informed consent in accordance with the Declaration of Helsinki. Ethics Commission of the Medical Faculty of the University of Münster, Germany, approved the study protocol.

### Stimuli

Two separate sinusoidal tones of 276 Hz and 250 Hz were presented dichotically to the left and right or right and left ears, resulting in binaural beat perception of 26 Hz (Fig. 1A). The tone duration was 500 ms, including 10 ms rise and decay times. Fig. 2A depicts the periodical fluctuation (increment and decrement) between the two dichotically presented prime tones (250 Hz and 276 Hz) resulting in 26 Hz amplitude



**Fig. 1.** Experimental design. A: A separate presentation of 250 Hz and 276 Hz stimuli to the left and right ears or vice versa results in a 26 Hz beat perception. B: Schema of the oddball paradigm used in the present research and its expected effects. At the bottom of the schema: sequence of binaural beats presented to the left and right ears. In the case of the deviant stimulus the tones are switched between the ears. In the middle: binaural interactions in the structures of brainstem. On the top: the cortical responses to the beats after the binaural interactions. The question mark assigns to the exploratory hypotheses of this work (see Introduction section).

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