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Comprehensive auditory discrimination profiles recorded with a fast parametric musical multi-feature mismatch negativity paradigm

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HIGHLIGHTS

- MMNs to 16 out of 18 types of sound feature change (pitch, timbre, location, intensity, slide and rhythm) at three levels of magnitude are elicited even in the complex musical sounding stimuli.
- For pitch, intensity, location, and slide, the MMN amplitude increased with increasing magnitude of feature change.
- The MMN amplitude and latency to slide correlated with melody or rhythmic musical skills, respectively, even in musically untrained participants.

ABSTRACT

Objective: Mismatch negativity (MMN), a component of the auditory event-related potential (ERP) in response to auditory-expectancy violation, is sensitive to central auditory processing deficits associated with several clinical conditions and to auditory skills deriving from musical expertise. This sensitivity is more evident for stimuli integrated in complex sound contexts. This study tested whether increasing magnitudes of deviation (levels) entail increasing MMN amplitude (or decreasing latency), aiming to create a balanced version of the musical multi-feature paradigm towards measurement of extensive auditory discrimination profiles in auditory expertise or deficits.
Methods: Using electroencephalography, we measured MMNs in healthy young adults to six types of sound feature change (pitch, timbre, location, intensity, slide and rhythm) at three different magnitudes of deviation, embedded in a music-sounding context. We also behaviourally assessed the individual musical aptitude using the Musical Ear Test (MET).
Results: 16 of 18 sound feature changes elicited significant MMNs. For pitch, intensity, location, and slide, the MMN amplitude increased with increasing magnitude of feature change. We observed a ceiling effect for rhythm, and a floor effect for timbre. The slide MMN amplitude correlated positively with MET melody score and negatively with MET rhythm score.
Conclusions: This novel paradigm provides an extensive, objective measure of auditory discrimination profile for different sound features embedded in a complex sound context.
Significance: The paradigm can be adopted to study the neurophysiology of individuals with music processing difficulties or with special musical skills, and may be a useful tool for investigating development, plasticity, and deficits of auditory processing.
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1. Introduction

The mismatch negativity (MMN) (Näätänen et al., 1978) is a component of the auditory event-related potential (ERP) recorded with electroencephalography (EEG) or magnetoencephalography (MEG), that has been related to violation of expectancy in sound features such as pitch, timbre, location of sound source, intensity, rhythm or to deviations of abstract auditory rules (Näätänen, 1992; Näätänen et al., 2001). The MMN peaks around 100–200 ms after violation onset and its amplitude and latency depend on deviation magnitude and are related to perceptual discriminability,

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such that larger deviations yield MMN components with higher amplitude and shorter latency (Näätänen et al., 1987a). The amplitude and latency of the MMN correlate with auditory behavioural measures, such as reaction time and hit rate in pitch discrimination tasks (Sams et al., 1985; Lang et al., 1990; Tiitinen et al., 1994; Novitski et al., 2004). Furthermore, the MMN is sensitive to discrimination learning (Näätänen et al., 1993) and hereby also to musical expertise (Tervaniemi, 2009).

The MMN provides an objective measure of auditory capabilities since it is pre-attentively elicited requiring neither subject's behavioural response nor attention towards the sounds (Näätänen et al., 1978; Alho, 1992; Paavilainen et al., 1993). Thereby, it is possible to avoid confounding factors such as differences between intervention groups and normal controls with respect to familiarity with, and motivation in relation to performing auditory tasks. Moreover, the MMN can be measured from people from whom it is difficult or even impossible to obtain reliable behavioural measures, for instance from aphasic (Csepe et al., 2001; Ilvonen et al., 2004) and comatose patients (Kane et al., 1993; Chausson et al., 2008), newborns (Alho et al., 1990; Winkler et al., 2009), and foetuses (Cheour-Luhtanen et al., 1996; Draganova et al., 2005). Hence, while its reliability at the individual level has still to be improved (e.g., Escera et al., 2000), the MMN represents a potentially useful tool for an objective, clinical evaluation of auditory discrimination functions at group level.

The MMN is affected in a number of different clinical conditions. This is the case for patients with impairment of the auditory system, such as for Cochlear Implant: a recent study by Sandmann (2010) successfully used the 'Optimum-1' MMN-paradigm developed by Näätänen and colleagues (Näätänen et al., 2004; Pakarinen et al., 2007), showing that MMNs can be elicited in CI users, although only for larger deviations as opposite to normal hearing subjects. Altered central auditory processing indicated by the MMN, despite intact peripheral hearing, has also been shown in such diseases as schizophrenia (Catts et al., 1995; Michie et al., 2002), Alzheimer's disease (Pekkonen et al., 1994; Riekkinen et al., 1997), AIDS (Schroeder et al., 1994), and diabetes (Vanhanen et al., 1996) and may also be a result of normal ageing (Pekkonen et al., 1996; Gaeta et al., 1998; Bertoli et al., 2002). Clinical groups may differ in their sensitivity to the magnitude of stimulus deviance. Baldeweg et al. (1999) found that in dyslexic adults, the MMN amplitude was attenuated only for smaller frequency changes, whereas the MMN amplitude for a larger frequency change and to moderate to large duration changes were comparable to those of controls. The auditory impairment may also be selective to a specific type of deviation (e.g., frequency, duration, intensity, phoneme). In children with dysphasia, the MMN amplitude for frequency change is more attenuated than for duration (Korpilahti and Lang, 1994). In contrast, a recent meta-analysis (Umbricht and Krljes, 2005) showed that in schizophrenia, the MMN amplitude to a change in the duration feature of a sound might be more attenuated than for a frequency change. In order to study such differential impairments directly, paradigms that incorporate more than one feature deviation as well as different magnitudes of these deviations are warranted.

The MMN has traditionally been recorded in 'oddball' paradigms where an occasional deviant is randomly introduced into sequences of standards (e.g., a note with a differing pitch height in a sequence of notes with a constant pitch; Näätänen, 1992). One of the disadvantages of the traditional MMN paradigms is that they test only for one type of sound deviant at a time, and that they present the deviants in a relatively simplified context. This limits the ecological validity of the results especially since recent MMN studies of auditory expertise indicate that the stimuli need to consist of realistic, complex musical material in order to disclose fine-grained processing differences between participants. When presented with simple sinusoidal tones with greater mistuning instead of fine-grained differences, violinists were not superior to non-musicians in discriminating pitch (Koelsch et al., 1999). A similar lack of MMN differences was obtained when examining the processing of isolated infrequent sinusoidal tones or of infrequent minor chords within a sequence of major chords in different kinds of musicians against non-musicians (Brattico et al., 2001, 2009; Fujioka et al., 2006; Seppänen et al., 2007). For instance, Seppänen et al. (2007) compared musicians who mainly employ auditory rehearsal and playing strategies to a non-aural group of musicians as determined by a questionnaire. Results showed that practice strategies modulate the speed of neural discrimination of interval and contour changes within melody-like patterns, but found no differences in the MMN to simple sound features. In many types of disorders characterised by atypical perception, such as autism, schizophrenia or congenital amusia, stimulus complexity is also a crucial factor (Näätänen et al., 2011). This emphasises the need for new paradigms presenting sound deviations in complex contexts for quantifying the capabilities of participants' or patients' auditory system. Furthermore, most MMN-paradigms are time-consuming (often exceeding an hour) which is impractical for clinical purposes, such as when studying MMN in children with attention deficits (Huttunen-Scott et al., 2008).

As a solution to this challenge, Näätänen and colleagues introduced a new multi-feature paradigm 'Optimum-1' in which MMNs are recorded for five different feature changes in less than 20 min (Näätänen et al., 2004). In the traditional oddball MMN paradigm, there are normally 80–90% repetitive standard stimuli and 10–20% deviants. Optimum-1 uses 50% standard sounds and 50% deviants. The standards alternate with different types of deviants, each differing from the standard in one acoustic feature only. The assumption is that the deviant stimuli reinforce the expectations for those features that they share with the standard. This allows for several MMNs to be independently elicited for different auditory attributes when they violate the predictions, making the duration of the experiment considerably reduced. Importantly, no difference is observed between the MMNs recorded with 'Optimum 1' and the ones obtained in the traditional 'oddball' paradigm for changes in sound duration, frequency, intensity, location and for sounds including an occasional short gap (Näätänen et al., 2004; Pakarinen et al., 2007).

We recently introduced a fast, musical multi-feature paradigm (Vuust et al., 2011) based on 'Optimum-1', measuring MMNs to six types of musical feature change (pitch, timbre, location, intensity, slide (Donington, 1974), and rhythm), embedded in a music sounding context in less than 20 min. Using this paradigm, we found quantitative and qualitative differences between pre-attentive discrimination of these features between musicians playing three distinct styles of music (classical, jazz, rock/pop) and non-musicians (Vuust et al., 2012a,b). Additionally, using a modified version of this paradigm, we have recently been able to record MMNs from CI-users to pitch, timbre, and intensity deviants (Timm et al., 2014).

In order to further develop the musical multi-feature paradigm, so that it is feasible for measuring sound discrimination expertise as well as deficits in complex sound contexts, we need to solve two problems. First, it is important to test whether the magnitude of sound feature changes correlates with the magnitude of the amplitude and the peak latency of the respective MMNs, when these changes occur in this complex sound context. Previous research indicates increasing amplitude and decreasing latency of the MMN for greater magnitude of sound deviation in a simpler context (Näätänen, 1992; Näätänen and Winkler, 1999; Novitski et al., 2004). Recent research (Horvath et al., 2008) further indicates that the effect of deviation magnitude on the MMN average may reflect the percentage of detected deviants, rather than a dif-

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