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RESEARCH ARTICLE

The event-related potential component P3a is diminished by identical deviance repetition, but not by non-identical repetitions

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Abstract

Mismatch negativity (MMN) represents an event-related potential (ERP) component which is elicited by deviant sound events in an otherwise regular, repetitive stimulation. The MMN amplitude typically decreases when two identical deviants are presented in direct succession, but it remains stable when the two deviants vary from the standard in different features. Less is known about such repetition effects on another ERP component, the P3a, which usually follows the MMN. In the current study, we investigated how the P3a was affected by identical and non-identical repetitions of sound deviants. The ERP analysis revealed that the P3a amplitudes were strongly diminished when the repeated deviants were identical, but the P3a remained stable when the repeated deviants varied. The findings suggest that not only the deviance detection system, as reflected in the MMN, but also subsequent attention switch systems, as reflected in the P3a, operate independently across different sound features.

Keywords Attention · Event-related potentials · Mismatch negativity · Prefrontal cortex · Predictive coding

Introduction

The mismatch negativity (MMN) represents an event-related potential (ERP) component that is elicited by sounds that deviate from an otherwise regular, repetitive auditory stimulation, even when subjects do not pay attention to the sounds (Näätänen et al. 1978). Sams et al. (1984) were the first to show that immediately repeated presentation of identical deviants leads to strongly diminished MMN amplitudes. Based on the prevailing sensory memory account of the MMN (for review Näätänen and Alho 1995; Schröger 1997), the authors suggested that the presentation of a deviant leads to decay of the memory trace of the standard tone and the renewed presentation would therefore result in weaker MMN responses, as compared to the initial one. Only few studies subsequently investigated such repetition effects, but all these studies revealed strongly diminished MMN amplitudes for repeated deviants (Deacon et al. 2000; Müller et al. 2005a, b; Müller and Schröger 2007), except when the repeated deviant together with a standard forms a different auditory object, which again violates the regularity of the auditory stimulation (Müller and Schröger 2007). The MMN to frequency deviants is also diminished when the frequency of the second deviant varies from the first (Deacon et al. 2000; Müller et al. 2005a).

In contrast, repetitions of qualitatively different deviants (e.g., a frequency deviant following a duration deviant) elicit MMN amplitudes of the same magnitude, as when presented in isolation (Nousak et al. 1996). This observation led to the suggestion that the presentation of a deviant solely affects the memory strength for the feature in which the deviant varies from the standard, but not the memory strength of features the deviant shares with the standard (Nousak et al. 1996). With regard to the predictive coding account of the MMN (Friston 2005; Winkler 2007), one may conclude that extracted rules and predictions are feature specific, and not stimulus specific. This feature specificity of the MMN is utilized in multi-feature paradigms, in which different

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kinds of deviants are presented within the same recording block. In such paradigms, the MMN can be observed with equal amplitude as in traditional oddball paradigms (e.g., Näätänen et al. 2004; Pakarinen et al. 2009; Partanen et al. 2013), interestingly even when the standards are omitted and only deviants are consecutively presented (Pakarinen et al. 2010).

As an exception from this rule, the MMN amplitude to the second deviant can be reduced when two different deviants are conditionally presented in a row, i.e., one kind of deviant always follows another (Todd and Mullens 2011; Todd et al. 2010, 2014; Todd and Robinson 2010). This effect is explained by the extraction of a sequence rule after the repeated exposure to the sequences of two deviants. To sum up, with the latter exception, the MMN amplitude is widely unaffected by immediate repetitions of non-identical, qualitatively different deviants, whereas it is usually suppressed by immediate repetitions of two identical deviants (or of two deviants of the same kind). Please note that two different deviants elicit just a singular MMN when the deviants are presented in short succession (< 200 ms) and form a conjoint auditory object (e.g., Winkler et al. 1998; Sussman et al. 1999; Jacobsen et al. 2013).

In contrast to the described repetition effects on the MMN, it is not fully clear how the subsequent ERP component P3a, which is considered to reflect an attention switch following the detection of an auditory mismatch (Näätänen 1990; Escera et al. 2000), is affected by deviance repetition: visual inspection of the ERP data provided by Müller et al. (2005a, Fig. 2) suggests that the presentation of two identical deviants in a row is associated, along with a reduction of the MMN, with a reduction of the P3a amplitude. More direct evidence for such a P3a decrease comes from the study of Horváth et al. (2008). These authors showed by an analysis of micro-sequences that the P3a amplitude is reduced for two immediately repeated change trials ('CC trials'), as compared to sequences in which the repeated sound was interspersed between the two change trials.

The effects of immediate non-identical deviance repetition were, to the best of our knowledge, only addressed in the study of Todd and Mullens (2011), in which the conditional presentation of two different deviants in a row was associated with increased P3a amplitudes to the second deviant. The finding is insofar somewhat surprising as predictability of the timing of the sound deviance usually decreases the P3a (e.g., Sussman et al. 2003; Horváth and Bendixen 2012; Volosin and Horváth 2014; Lecaignard et al. 2015). Todd and Mullens (2011) themselves referred the observed P3a increase to the higher number of standards preceding deviants in linked sequences (conditional presentation), as compared to the unconditional presentation. A decrease of the P3a amplitude by more predictable stimuli would be in line with hierarchical predictive coding accounts, which assume that the brain encodes the causal/temporal structure of sensory stimulation on multiple hierarchical levels (Friston 2005; Friston and Kiebel 2009). Bekinschtein et al. (2009) suggested that the posteriorly distributed P3b reflects prediction processes related to more global rules, whereas the MMN reflects temporally and conceptually more limited processes (see also Wacongne et al. 2011; Strauss et al. 2015). These authors assumed that the P3a also relates to local rules and is elicited automatically after the MMN, but they did not further define the functional coupling of MMN and P3a-related cognitive processes (Bekinschtein et al. 2009; Wacongne et al. 2011; Strauss et al. 2015).

In the current study, we aimed at comparing the effects of identical and non-identical deviance repetition on the P3a, as opposed to the effects on the MMN. In our main experiment ('Experiment 1'), two different deviants were presented within the same block, one frequency and one duration deviant. Each kind of deviant was presented either in isolation, preceding another deviant, or succeeding another deviant, all with the same likelihood (Fig. 1). Whereas the occurrences of isolated and initial deviants were hardly predictable, two of three deviants were succeeded by another deviant: Thus, after a deviant, there was a 2:1 chance that a second deviant was presented than that a standard was presented. We hypothesized that under such conditions, not just the repeated presentation of deviants of identical deviants, but also of non-identical deviants would lead to a reduction of the P3a amplitude, due to the increased predictability of the second deviant. Moreover, as identical repetitions of two deviants were associated with decreased P3a amplitudes even when the timing was not predictable (Horváth et al. 2008), we hypothesized that the P3a amplitude would show a more pronounced decrease for identical vs. non-identical repetitions. Along with the modulation of the P3a with repeated deviants, we report on the modulation of the MMN by the experimental manipulation. For the MMN, we expected to replicate previous findings and to observe decreased MMN amplitudes for identical repetitions of deviants and unaffected MMN amplitudes for non-identical repetitions. After the initial experiment, we ran a second experiment ('Experiment 2') to rule out that some of the findings for identical repetitions were influenced by the simultaneous investigation of non-identical repetitions.

Experiment 1

Methods

Participants

22 volunteers (15 female) took part in the experiment. The mean age was 23.6 years (range 18–34 years). Participants

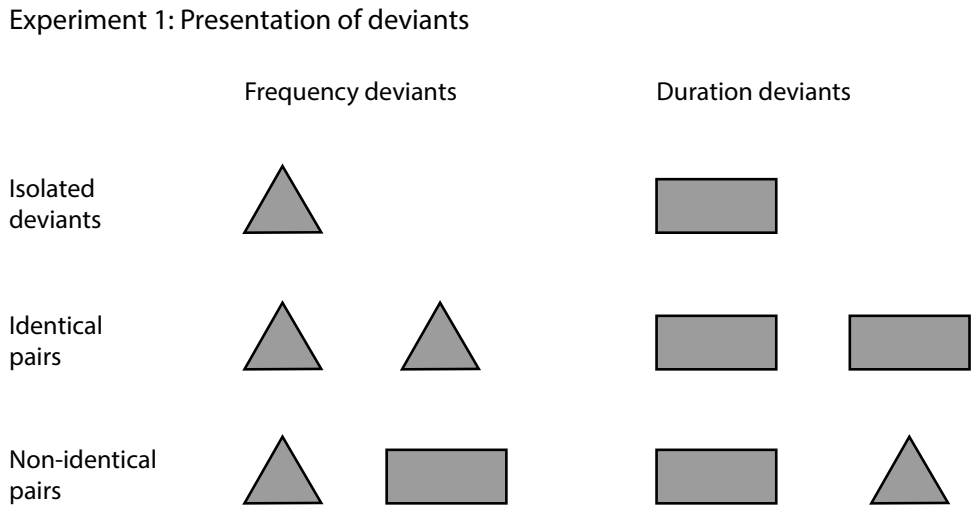

Fig. 1 Schematic view of the presentation of deviants in Experiment 1. Deviants were presented in isolation, in identical pairs or non-identical pairs. The effects of identical deviance repetition were investigated within identical pairs; the effects of non-identical deviance repetition were investigated across non-identical pairs, e.g., by contrasting the MMN to the initial duration deviant (followed by a frequency deviant) with the MMN to the duration deviant, preceded by a frequency deviant. The likelihood for all combinations was the same (3%). Non-identical pairs were not presented in Experiment 2

were, with few exceptions, psychology students of the Saarland University, who were compensated for their participation with course credit points. All participants were included in the data analysis. All subjects gave written informed consent before participation. The study was conducted in accordance with the ethical guidelines of psychological research, as formulated by the German Psychology Society ('Deutsche Gesellschaft für Psychologie', https://www.dgps.de/fileadmin/documents/ethikrl2004.pdf).

Stimulation

Three different stimuli were presented. The standard stimulus was a sinusoid tone (800 Hz, 50 ms duration). Two different sinusoid tones were used as deviants, one duration deviant (800 Hz, 100 ms duration) and one frequency deviant (880 Hz, 50 ms duration). All tones included a 5 ms fading in and fading out and were presented at approximately 70 dB sound pressure level, as measured by a digital sound level meter (Professional GM1351, Tiang Tech, Guangdong, China). Recordings took place in an electrically, but not acoustically shielded recording chamber. The experimenters monitored the recordings from outside the chamber and avoided any sounds during the recordings. Participants sat in an upright position in front of a computer screen and watched a video without sound. They were instructed to pay attention to the video material and to memorize the scenes for later memory tests. Participants were also instructed to sit relaxed and avoid facial, as well as body movements during the recordings. Auditory stimuli were presented by a pair of loudspeakers placed on the left and right side of the computer screen and were not related to any task. The memory tests took place after each block of auditory stimulation. In these tests, five scenes from the video were presented together with five unseen scenes and participants had to make an old/new decision for each scene. Of note, the memory task was solely implemented to make sure that the participants stayed awake and paid attention to the video.

The two different deviants were presented within the same blocks: isolated, preceding an identical deviant, succeeding an identical deviant, preceding a different deviant or succeeding a different deviant, as depicted in Fig. 1. The likelihood for all pairings was 3% each. The overall likelihood for the two kinds of deviants was 15% each (=5 combinations x 3%) and the likelihood for standards was 70%. There were three blocks with 1000 stimuli each. At least two standards preceded isolated deviants and the initial deviants in pairs. Tones were presented at a stimulus-onset asynchrony (SOA) of 1012 ms.

EEG recording

EEG was recorded from 28 silver/silver chloride electrodes (Fp1, Fp2, F7, F3, Fz, F4, F8, FC5, FC3, FCz, FC4, FC6, T7, C3, Cz, C4, T8, CP3, CPz, CP4, P7, P3, Pz, P4, P8, O1, O2, M2) with a sampling rate of 500 Hz, referenced to the left mastoid (M1). All EEG electrodes (but the mastoid electrodes) were embedded in an electrode cap (Easycap, Herrsching, Germany). In addition to EEG, vertical and horizontal electroocular activity was recorded from two pairs of electrodes, one pair placed above and below the right eye and one pair placed on the left and right outer canthi. Data

were filtered online from 0.016 Hz (time constant 10 s) to 250 Hz. Electrode impedances were kept < 5 kΩ.

EEG data analysis

EEG data were analyzed by means of the BrainVision Analyzer 2.1.0 (Brain Products, Gilching, Germany). EEG data were initially filtered with 0.5 Hz (24 dB/oct) high pass. Subsequently, all EEG data exceeding ± 300 µV were excluded. To correct ocular artifacts, an independent component analysis (ICA) was run; artifacts stemming from blinks, lateral eye movements, heart activity (electrocardiographic artifacts) and pronounced electromyographic activity were identified and removed. After the ICA correction, data were low pass filtered at 30 Hz (48 dB/oct). Line activity was eliminated by an additional notch filter at 50 Hz. EEG was re-referenced to linked mastoids (M1, M2). The EEG was segmented into epochs of 1000 ms length, including a 200 ms pre-stimulus baseline, and baseline corrected. Epochs with signals exceeding ± 70 µV were excluded from the data analysis. Epochs in response to standards, standards following deviants, and deviants were selectively averaged. To visualize the MMN and P3a and to identify the peaks of these two components, ERPs to standards were subtracted from ERPs to deviants (Fig. 2).

The mean P3a amplitudes for frequency and duration deviants were extracted in 60-ms time windows symmetrically placed around the P3a peak amplitudes, as determined by the grand average of the difference potentials to isolated deviants at electrode FCz. The mean MMN amplitudes were quantified analogously. Specifically, the P3a amplitudes to frequency deviants were determined from 220 to 280 ms, and the P3a amplitudes to duration deviants from 236 to 296 ms, the MMN amplitudes to frequency deviants from 132 to 192 ms, and the MMN amplitudes to duration deviants from 140 to 200 ms (Fig. 2). Both the MMN and P3a

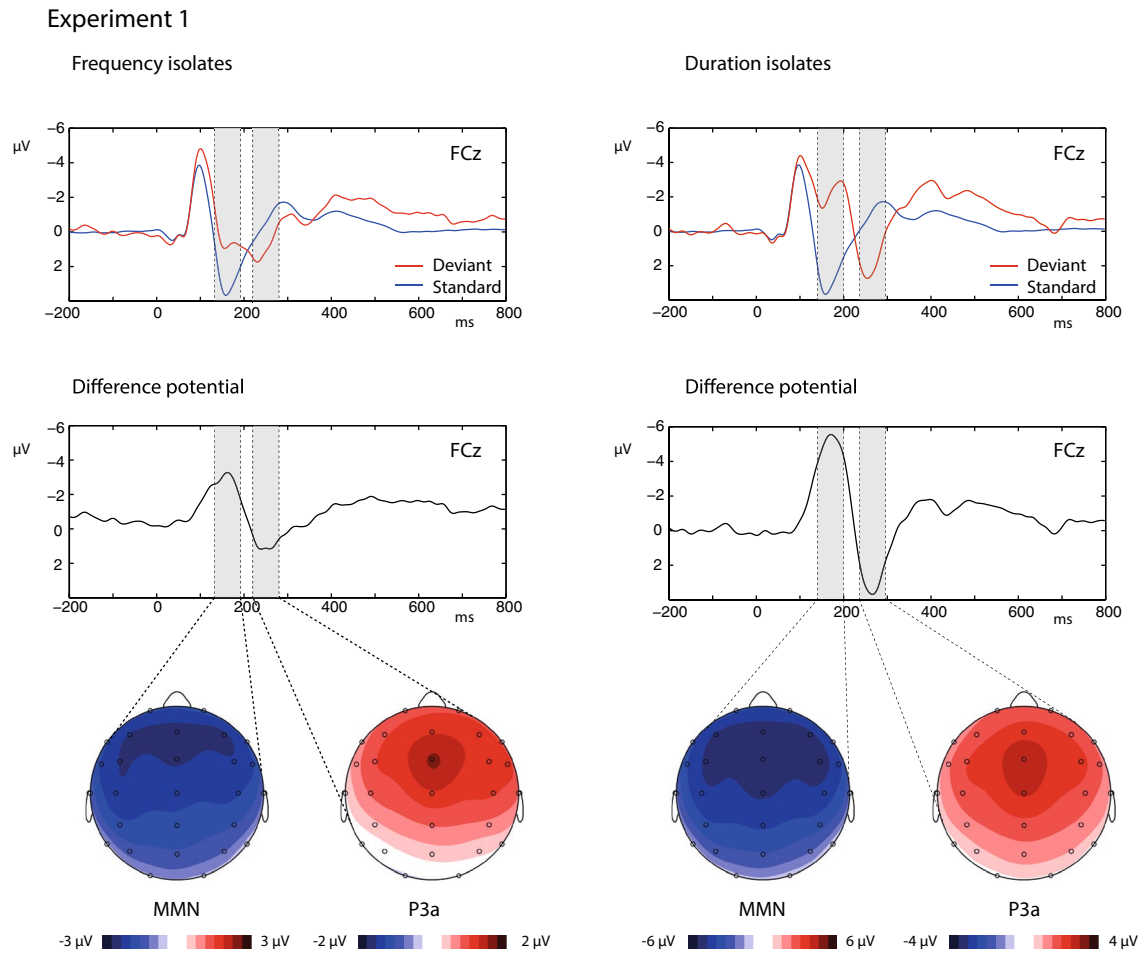

Fig. 2 Top: ERPs to standards (blue line) and deviants (red line) at electrode FCz, for each of the two kinds of deviants separately (left: frequency deviants; right: duration deviants); middle: the difference potentials (ERPs to deviants—ERPs to standards) for frequency deviants (left) and duration deviants (right); the latency ranges used for the quantification of the MMN and P3a amplitudes are marked by gray shading; bottom: topographic maps of the MMN and P3a for each of the two deviants. Negativity is plotted upwards

were maximal at FCz. Only data from this electrode were considered for the data analysis.

Statistics

The P3a and MMN amplitudes were separately subjected to a repeated-measure analysis of variance (ANOVA) with POSITION (1st vs. 2nd deviant), CONDITION (identical vs. non-identical repetition), and DEVIANCE (frequency vs. duration) as within-subject factors. The effects of identical repetition were investigated by contrasting the P3a/MMN of the initial deviant and of the repeated deviant within identical pairs, whereas the effects of non-identical repetition were investigated by contrasting the P3a/MMN of the initial deviant and of the repeated deviant across non-identical pairs. ERP responses to isolated deviants were not considered in the analysis, but were used to determine the latency windows for the P3a and MMN. In a separate analysis, we revealed that the P3a and MMN amplitudes did not vary between isolated and initial deviants, as intended by the experimental design (data not shown).

Results

The ERPs to isolated deviants and standards are depicted in Fig. 2 (top). The difference potential exhibited an MMN followed by a P3a, both with their typical midfrontal maxima (Fig. 2, bottom). The P3a and MMN amplitudes to duration deviants were considerably larger than to frequency deviants. The descriptive data (P3a and MMN amplitudes) are found in Tables 1 and 2.

Repetition effects on the P3a amplitude The ANOVA revealed significant main effects of POSITION (1st vs. 2nd deviant; $F_{1,21} = 44.121$, $p < 0.001$, $\eta^2 = 0.678$), CONDITION (identical vs. non-identical repetition; $F_{1,21} = 11.058$, $p = 0.003$, $\eta^2 = 0.345$) and DEVIANCE (frequency vs. duration; $F_{1,21} = 22.106$, $p < 0.001$, $\eta^2 = 0.513$). Moreover, there was a significant POSITION × CONDITION interaction ($F_{1,21} = 28.478$, $p < 0.001$, $\eta^2 = 0.576$), indicating that the repetition effects varied between identical and non-identical repetitions of deviants. Other interactions did not reach significance (all $F_{1,21} < 1$, all $\eta^2 < 0.03$). The POSITION × CONDITION interaction was followed up by analyzing the effects of POSITION and DEVIANCE in each condition:

For identical repetitions, the P3a amplitudes of repeated duration and frequency deviants were strongly diminished, as compared to the initial presentation of the same deviant (main effect of POSITION: $F_{1,21} = 53.285$, $p < 0.001$, $\eta^2 = 0.717$, Table 1, Fig. 3). This repetition effect did not significantly vary between the two kinds of deviants, as suggested by a non-significant POSITION × DEVIANCE interaction ($F_{1,21} = 1.002$, n.s., $\eta^2 = 0.046$). However, the P3a amplitudes to duration deviants were in general significantly

Table 1 Mean P3a amplitudes (± SD)

Deviant	Exp	Isolate	Identical pairs			Non-identical pairs	
			1st deviant	2nd deviant		1st deviant	2nd deviant
Frequency	1	1.5 (1.3)	1.7 (1.5)	0.2 (1.3)	↓	1.4 (2.0)	1.7 (2.0)
	2	1.8 (1.7)	2.1 (2.1)	0.4 (1.4)	↓	–	–
Duration	1	3.0 (1.8)	3.3 (1.7)	1.3 (1.4)	↓	3.0 (1.7)	3.2 (2.0)
	2	3.8 (2.3)	3.9 (2.4)	1.2 (1.6)	↓	–	–

The P3a amplitudes of the two experiments, as indexed by the column 'Exp.', for the kinds of deviants. Identical pairs of deviants were presented in both experiments; non-identical pairs were only presented in Experiment 1. Significant amplitude decreases between the first and second deviant are marked with downward-directed arrows

Table 2 Mean MMN amplitudes (± SD)

Deviant	Exp	Isolate	Identical pairs			Non-identical pairs		
			1st deviant	2nd deviant		1st deviant	2nd deviant	
Frequency	1	− 2.3 (1.7)	− 2.0 (2.0)	− 2.0 (1.2)		− 2.3 (1.5)	− 3.2 (1.8)	↑
	2	− 3.2 (1.7)	− 3.0 (1.7)	− 3.1 (1.4)		–	–	
Duration	1	− 5.0 (2.0)	− 5.0 (1.7)	− 4.4 (1.7)	↓	− 5.5 (1.9)	− 5.0 (1.7)	
	2	− 5.7 (1.9)	− 5.9 (1.7)	− 4.9 (2.1)	↓	–	–	

The MMN amplitudes of the two experiments, as indexed by the column 'Exp.', for the two kinds of deviants. Identical pairs of deviants were presented in both experiments; non-identical pairs were only presented in Experiment 1. Significant amplitude decreases between the first and second deviant are marked with downward-directed arrows, increases with upward-directed arrows

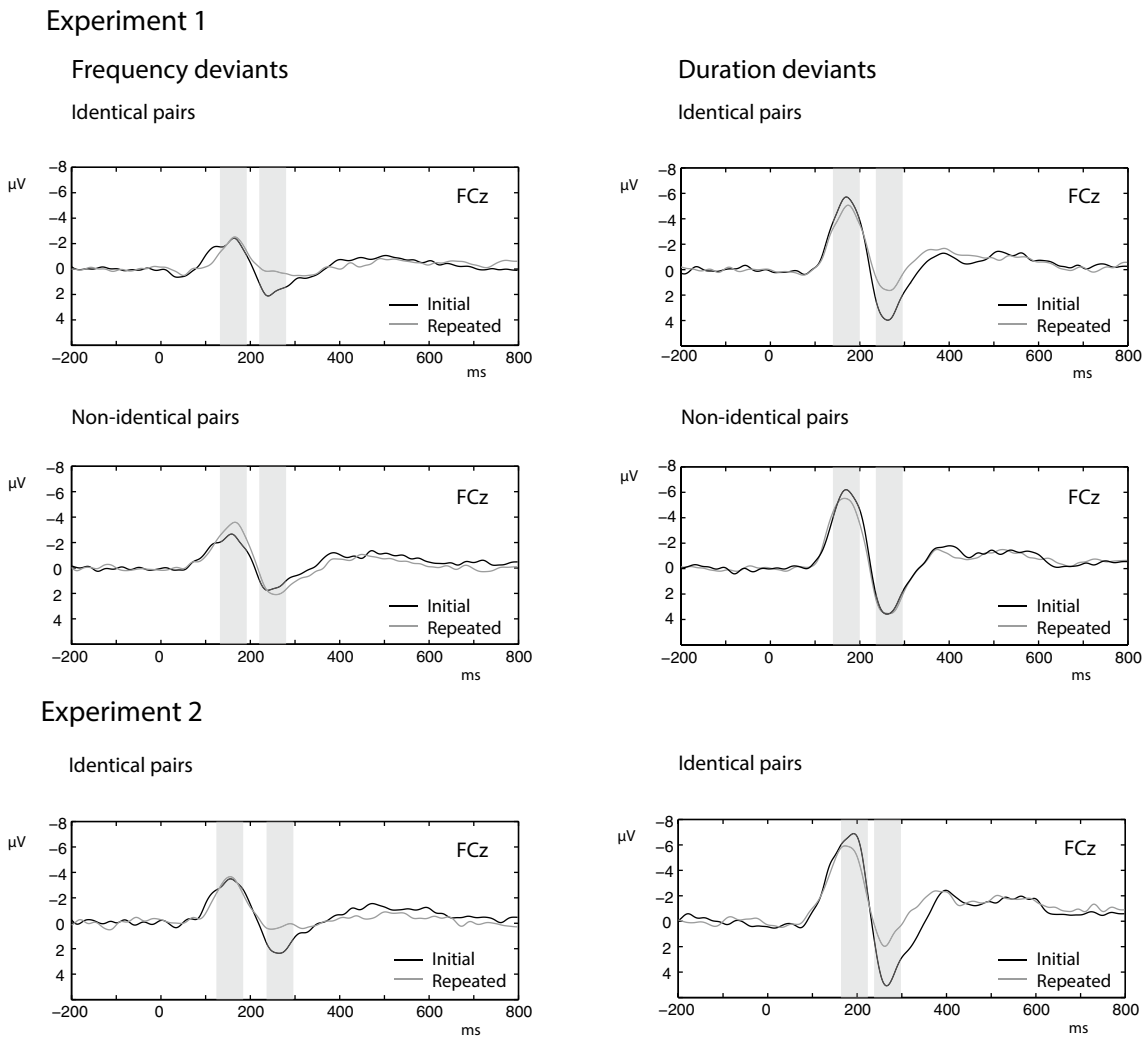

Fig. 3 The difference potentials (ERPs to deviants—ERPs to standards) to the initial deviant (black line) and to the subsequent deviants (gray line) for frequency and duration deviants (left column and right column, respectively); the latency ranges used for the quantification of the MMN and P3a amplitudes are marked by gray shading; in Experiment 1, a deviant could be followed by either a duration or frequency deviant, i.e., there were identical and non-identical repetitions; in Experiment 2, a deviant could only be followed by an identical deviant. The non-identical repetition effects were studied by contrasting the difference potentials across pairings. Please note that particularly the P3a and much less the MMN amplitudes were affected by identical deviance repetition. These effects were highly similar in both experiments. Non-identical repetition did not diminish the MMN and P3a amplitudes

larger than the P3a amplitudes to frequency deviants (main effect of DEVIANCE: $F_{1,21} = 23.098$, $p < 0.001$, $\eta^2 = 0.524$).

For non-identical repetitions, the P3a amplitudes were stable when two different deviants were presented in succession (Table 1; Fig. 3). POSITION had no impact on the P3a amplitude, neither alone ($F_{1,21} = 0.928$, n.s., $\eta^2 = 0.042$) nor in interaction with DEVIANCE ($F_{1,21} = 0.020$, n.s., $\eta^2 = 0.001$). The P3a amplitudes to duration deviants were in general significantly larger than the P3a amplitudes to frequency deviants (main effect of DEVIANCE: $F_{1,21} = 13.752$, $p = 0.001$, $\eta^2 = 0.396$).

Repetition effects on the MMN amplitude The ANOVA revealed significant main effects of CONDITION ($F_{1,21} = 17.057$, $p < 0.001$, $\eta^2 = 0.448$) and DEVIANCE (frequency vs. duration; $F_{1,21} = 102.944$, $p < 0.001$, $\eta^2 = 0.831$), but not for POSITION ($F_{1,21} = 0.019$, n.s., $\eta^2 = 0.001$). However, there was a significant POSITION × DEVIANCE interaction ($F_{1,21} = 10.388$, $p = 0.004$, $\eta^2 = 0.331$), indicating that the repetition effects varied between the two kinds of deviants. Other interactions did not reach significance (all $F_{1,21} < 1.860$, n.s. all $\eta^2 < 0.082$). The POSITION × DEVIANCE interaction was followed up by analyzing the effects of POSITION and CONDITION for the two kinds of deviants separately.

For duration deviants, the MMN amplitude decreased when deviants were repeated (main effect of POSITION:

$F_{1,21} = 9.560$, $p = 0.006$, $\eta^2 = 0.313$). This effect did unexpectedly not vary between identical and non-identical repetitions, as suggested by a non-significant CONDITION × POSITION interaction ($F_{1,21} = 0.133$, n.s., $\eta^2 = 0.006$). Within the two conditions, the MMN amplitude of duration deviants showed similar decreases when deviants were repeated (identical repetition: $t_{21} = 2.147$, $p = 0.044$, $d = 0.459$; non-identical repetition: $t_{21} = 1.722$, n.s., $d = 0.369$). Moreover, the MMN amplitudes were generally larger for non-identical repetitions than for identical repetitions (main effects of CONDITION: $F_{1,21} = 15.877$, $p = 0.001$, $\eta^2 = 0.431$).

For frequency deviants, the MMN amplitude marginally varied when deviants were repeated (main effect of POSITION: $F_{1,21} = 2.997$, $p = 0.098$, $\eta^2 = 0.125$; CONDITION × POSITION interaction: $F_{1,21} = 2.863$, n.s., $\eta^2 = 0.120$). The MMN amplitudes were generally larger for non-identical repetitions than for identical repetitions (main effect of CONDITION: $F_{1,21} = 9.830$, $p = 0.005$, $\eta^2 = 0.341$). To further clarify the result pattern, follow-up tests were run within each condition, even though they were not licensed by a significant CONDITION × POSITION interaction. The observed trend effect for POSITION primarily reflected an increase of the MMN amplitude, which was present when frequency deviants succeeded duration deviants ($t_{21} = 2.652$, $p = 0.015$, $d = 0.570$), whereas the MMN amplitude remained widely stable when two frequency deviants occurred in succession ($t_{21} = 0.177$, n.s., $d = 0.039$). The observed CONDITION effect was primarily due to the increased MMN amplitudes for non-identical repetitions as compared to identical repetitions ($t_{21} = 3.231$, $p = 0.004$, $d = 0.714$). The MMN to initial frequency deviants did not vary between conditions ($t_{21} = 0.938$, n.s., $d = 0.208$).

Preliminary discussion of experiment 1

For the P3a, a clear pattern of results was revealed. Strong amplitude reductions were observed for identical repetitions, whereas the P3a amplitudes remained stable when two different deviants were presented in succession. The findings did not vary between the two kinds of deviants. For the MMN, the repetition effects were indistinct. For duration deviants, identical repetition was associated with small MMN amplitude decreases. However, there was no MMN amplitude decrease for two frequency deviants in succession. The latter finding was quite unexpected, as previous studies reported large effects of identical repetitions of frequency deviants on the MMN amplitude (Sams et al. 1984; Deacon et al. 2000; Müller et al. 2005a, b; Müller and Schröger 2007). As a possible reason for the unexpected finding, we assumed that the mixed presentation of duration and frequency deviants might in some way have had an impact on the results. Therefore, we ran another experiment in which frequency and duration deviants were presented in separate blocks. In this second experiment, only the effects of identical repetition were studied in an attempt to evoke the pronounced repetition effects on the MMN amplitude, as previously reported in the literature.

Experiment 2

Methods

Participants

22 volunteers (15 female) took part in Experiment 2. The mean age was 24.3 years (range 19–33 years). 15 participants of Experiment 1 took part in Experiment 2.

Stimulation

Stimuli and SOA were the same as used in Experiment 1. In contrast to Experiment 1, the two kinds of deviants were presented in separate blocks. Within each block, deviants could occur isolated, preceding an identical deviant or succeeding an identical deviant, with 5% likelihood. Thus, within a block the likelihood for frequency or duration deviants was 15%, and the likelihood for standards was 85%. Blocks with duration and frequency deviants were alternately presented; the order of blocks was balanced across participants. There were four blocks with 900 stimuli each. Participants watched a silent video and were again instructed to memorize its contents.

EEG recording and data analysis

The technical parameters of the EEG recordings were the same as in Experiment 1. The data were analyzed analogously to Experiment 1. The latency windows used for the ERP data analysis slightly varied between the two experiments. For Experiment 2, the P3a amplitudes to frequency deviants were determined from 236 to 296 ms, the P3a amplitudes to duration deviants from 238 to 298 ms, the MMN amplitudes to frequency deviants from 124 to 184 ms and the MMN amplitudes to duration deviants from 164 to 224 ms at electrode FCz.

Statistics

The MMN and P3a amplitudes at FCz were separately subjected to a repeated-measure ANOVA with POSITION (1st vs. 2nd deviant) and DEVIANCE (frequency vs. duration) as within-subject factors. To clarify the potential impact of the experimental design on the findings directly, the results of the 15 participants who took part in both experiments were

directly contrasted by a repeated-measure ANOVA with POSITION, DEVIANCE, and EXPERIMENT (Experiment 1 vs. Experiment 2) as within-subject factors.

Results

P3a As already observed in Experiment 1, the P3a amplitudes were strongly diminished when two identical deviants were presented in direct succession (main effect of POSITION: $F_{1,21} = 6.355$, $p < 0.001$, $\eta^2 = 0.768$). The POSITION × DEVIANCE interaction was also significant ($F_{1,21} = 4.578$, $p = 0.044$, $\eta^2 = 0.179$), which was due to a slightly more pronounced P3a decrease for repeated duration deviants ($t_{21} = 7.819$, $p < 0.001$, $d = 1.894$), as compared to frequency deviants ($t_{21} = 4.900$, $p < 0.001$, $d = 1.127$). Again similar to Experiment 1, the P3a amplitudes of duration deviants were in general significantly larger than the P3a amplitudes of frequency deviants (main effect of DEVIANCE: $F_{1,21} = 15.379$, $p < 0.001$, $\eta^2 = 0.423$).

MMN A marginally significant main effect of POSITION ($F_{1,21} = 3.376$, $p = 0.080$, $\eta^2 = 0.139$), significant main effect of DEVIANCE ($F_{1,21} = 45.826$, $p < 0.001$, $\eta^2 = 0.686$), and significant POSITION × DEVIANCE interaction ($F_{1,21} = 10.195$, $p = 0.004$, $\eta^2 = 0.327$) were revealed. The latter interaction was further investigated by comparing the MMN of the two kinds of deviants between the initial and repeated presentations. For duration deviants, there was a significant decrease of the MMN amplitude when deviants were repeated ($t_{21} = 3.731$, $p = 0.001$, $d = 0.827$), whereas there was no such decrease for frequency deviants ($t_{21} = 0.141$, n.s., $d = 0.031$).

Experiment 1 vs. Experiment 2 The comparison of the P3a and MMN results between the two experiments revealed significant main effects of EXPERIMENT (P3a: $F_{1,14} = 12.545$, $p = 0.003$, $\eta^2 = 0.473$; MMN: $F_{1,14} = 9.565$, $p = 0.008$, $\eta^2 = 0.406$), indicating larger MMN and P3a amplitudes in Experiment 2. However, there were neither significant interactions between EXPERIMENT × POSITION nor between EXPERIMENT × POSITION × DEVIANT (all $F_{1,14} < 2.161$, n.s., all $\eta^2 < 0.135$), suggesting that the POSITION effects were not modulated by the experimental setup.

Preliminary discussion of experiment 2

In Experiment 2, the effects of identical repetitions were highly similar to Experiment 1. Thus, contrary to our assumption, the mixed presentation of duration and frequency deviants had no substantial impact on the results of Experiment 1 on identical repetitions. In particular, the lack of pronounced repetition effects on the MMN amplitude for frequency deviants cannot be explained by the mixed presentation of the two deviants.

General discussion

P3a amplitude decrease for identical and non-identical pairs

In the current study, we sought to investigate the effects of deviance repetition on the P3a. Based on the predictive coding accounts (Friston 2005; Friston and Kiebel 2009) and on empirical findings by Müller et al. (2005a) and Horváth et al. (2008), we hypothesized that the P3a amplitude would be reduced with repeated presentation of two identical deviants. Confirming this hypothesis, we observed pronounced P3a amplitude decreases under such conditions for frequency and duration deviants. Of note, in contrast to the study of Müller et al. (2005a), there was no decrease of the MMN amplitude for repeated frequency deviants in our study. This finding suggests that the observed reduction of the P3a cannot be considered as a direct consequence of reduced automatic mismatch detection processes, as reflected in the MMN.

The relation between processes reflected in the MMN and P3a is still a matter of debate. An MMN is not always followed by a P3a and is thus not elicited automatically after each MMN, as sometimes stated (e.g., Strauss et al. 2015). Friedman et al. (2001, pg. 356) suggested that a stimulus needed to be "sufficiently deviant" to elicit a P3a. In line with this suggestion, P3a responses in multi-feature paradigms were not observed for conventional deviants (frequency, duration, or intensity deviants), but only for deviants strongly varying from the pure tone standard (white noise and environmental sound deviants) (Tavakoli and Campbell 2016). However, it is quite apparent from the current findings that the physical characteristics are only one aspect that contributes to the degree of the subjectively perceived deviance. Within identical deviant pairs, a P3a was observed for the initial deviant, but to a much lesser degree for the repeated deviant.

In another account for explaining the conditions that contribute to the P3a generation in auditory oddball tasks, Rinne et al. (2006) suggested that the P3a might just be generated when the sound deviance results in enhanced N1 activity. This assumption was based on their findings in a study, in which intensity deviants were used. They observed that intensity deviants louder than the standard elicited not just an MMN, but also an enhanced N1 and a P3a, whereas intensity deviants softer than the standard elicited an MMN, but no enhanced N1 and no P3a. In an additional analysis (see Supplementary material), we analyzed whether duration and frequency deviants were associated with increased N1 amplitudes, as compared to standards, and whether identical repetitions were associated with decreased N1 amplitudes, as one would expect according to the account of Rinne et al. (2006). For frequency deviants, we observed in both experiments that the N1 amplitude was increased as compared to

standards, except when the frequency deviant was presented after another frequency deviant. Moreover, there was an N1 decrease from the initial to the repeated frequency deviant in identical pairs. Thus, for repeated frequency deviants in identical pairs, the P3a was reduced when the N1 amplitude was reduced. However, there was no such clear pattern for duration deviants. In particular, there was no evidence for an N1 decrease for repeated duration deviants in identical pairs. Thus, for these deviants, the P3a was reduced even though the N1 amplitude remained stable. Given this, our study revealed only partial support for the account of Rinne et al. (2006).

Rather than considering this N1 modulation account of Rinne et al. (2006), we favor more a psychological explanation for the observed P3a modulation. Similar to us, Horváth et al. (2008) observed that the MMN and P3a are not strongly coupled processes of change detection. They proposed that the P3a does not solely reflect an attention switch process, but reflects processes related to the experienced significance of the deviant (or novel) event. In line with this significance account, it has been reported that the predictability of events diminishes P3a-related processes (Sussman et al. 2003; Horváth and Bendixen 2012; Volosin and Horváth 2014). Moreover, the P3a is reduced when novel events are repeated across recording blocks (Friedman et al. 2011). According to the significance account, one would argue the P3a is strongly diminished by a second deviant in identical pairs, as the kind of deviance has already been registered in the immediate past and the renewed presentation of this deviant bears in itself only little significance.

In contrast to identical pairs, the P3a amplitudes remained stable for non-identical pairs, even though two out of three initial deviants were followed by another deviant. This is contrary to our initial hypothesis that the increased predictability for all repeated deviants leads to decreased P3a responses. The preserved P3a amplitudes for non-identical pairs indicate that predictability alone has no major impact on the experienced significance of deviants. Thus, it appears that only the exact repetition of deviance, and not the higher predictability, triggers the lowered attention switch to repeated identical deviants. The finding on the P3a for non-identical repetitions mirrors the lack of such repetition effects on the MMN, as currently observed and previously reported (e.g., Nousak et al. 1996). The current findings suggest that not only the deviance detection system, but also subsequent attention switch systems operate independently across different sound features. With regard to hierarchical predictive coding models (Friston 2005; Friston and Kiebel 2009; Wacongne et al. 2011), findings suggest that detected prediction errors on a lower hierarchical level, as reflected in the MMN, might sometimes (under still to be defined conditions) override predictions formed on a higher hierarchical level and be associated with a preserved P3a. The two hierarchical levels are apparently only loosely or indirectly linked, as already discussed further above. However, hierarchical predictive coding models are rather complex (Friston 2005; Friston and Kiebel 2009). It needs to be stated that the here presented data are for two reasons not suited to disclose the network dynamic that may underlie the hierarchical organization of the MMN and P3a. First, the amplitudes of the two components reflect the summed activity of their underlying generators (e.g., Garrido et al. 2007). Secondly, the network dynamic might include other ERP components, such as middle-latency deviance-related ERP modulations (10–50 ms, for review Grimm et al. 2016) or the before mentioned deviance-related N1 modulation (Rinne et al. 2006), as well as oscillatory activity which is not directly reflected in ERP measures, such as theta band oscillations (Hsiao et al. 2009; Javitt et al. 2018) or gamma band brain network dynamics (Nicol et al. 2012).

The finding of an unchanged P3a for non-identical repetitions is at first glance in contrast to the study of Todd and Mullens (2011) who showed that the conditional presentation of two different deviants in a row was associated with increased P3a amplitudes to the second deviant. Todd and Mullens (2011) referred this increase to the higher number of standards preceding deviants in linked sequences (conditional presentation), as compared to the usual, random sequences (unconditional presentation). In the current study, the number of preceding standards did not vary between initial and repeated deviants; on the other hand, our study lacked conditionally linked sequences. Therefore, the findings of the two studies are difficult to compare. We might however note that the combination of reduced MMN amplitudes and increased P3a for duration deviants, as observed by Todd and Mullens (2011), is difficult reconcile with the P3a accounts of Friedman et al. (2001) and Horvath et al. (2008), as well as hierarchical predictive coding accounts (Friston 2005; Friston and Kiebel 2009; Wacongne et al. 2011).

Even though we claim that the P3a, similar to the MMN, operates independently across different sound features, we acknowledge that the P3a might have some tighter boundaries to be elicited than the MMN. For multi-feature paradigms, the P3a is, as outlined above, only observed for rather strong deviants, whereas the MMN is usually elicited by any kind of perceivable sound deviance (Tavakoli and Campbell 2016). Similar to the study of Tavakoli and Campbell (2016), only one of five deviants elicited a P3a in the study of Sorokin et al. (2010). The authors attributed the widely absent P3a to the characteristics of the multi-feature paradigm with its constant variation. In both studies (Sorokin et al. 2010; Tavakoli and Campbell 2016), 50% of the stimuli were standards and a standard was never followed by another standard. Under such conditions of constant variation, the P3a as orienting response might indeed be widely suppressed, as suggested by Sorokin

et al. (2010). We assume that this might be even more the case as the continuous virtual paired presentation of one standard and one deviant might form the prepotent perceived regularity of this kind of stimulation.

MMN amplitude decrease for identical pairs

In both of our experiments, the MMN amplitudes were either slightly reduced (duration deviants) or not at all reduced (frequency deviants), when two identical deviants were presented in a row. Our findings did, thus, not depend on whether the two kinds of deviants were presented in mixed or separate blocks, as we initially assumed.

Previous MMN studies did not investigate the effects of repeated duration deviance. Even though the observed decrease of the MMN amplitudes for such repetitions was less pronounced than the repetition effects on the P3a amplitudes and less pronounced than reported in the literature for the MMN to frequency deviants, the findings are still in good agreement with these previous reports (Sams et al. 1984; Müller et al. 2005a). However, for frequency deviants, we could not observe any repetition effects on the MMN, which is in stark contrast to previous studies, reporting amplitude decreases of 40–50% after identical repetitions (Sams et al. 1984; Deacon et al. 2000; Müller et al. 2005a). At this very moment, we cannot explain the absence of this effect in our study. The used stimulus material and other parameters of our experiment were comparable to at least one of the previous experiments: the used SOA (1012 ms) was close to the SOA (1000 ms) used by Sams et al. (1984), the conditional probability for repetitions (Experiment 1: 33%; Experiment 2: 50%) was similar/identical to the conditional probability (50%) used by Müller et al. (2005a), and the degree of frequency deviance was with 10% in the range of those previously used, which varied from 5 to 25% (Sams et al. 1984; Deacon et al. 2000; Müller et al. 2005a).

The only noteworthy peculiarity of the current study is that the MMN amplitudes for frequency deviants were, in particular in Experiment 1, relatively small as compared to previous studies, which was likely due to the combination of the relatively small degree of frequency deviance and relatively high likelihood for deviants. However, in Experiment 2, the MMN amplitudes to frequency deviants were larger than in Experiment 1, but still there was no effect for identically repeated frequency deviants. Thus, we do not consider the magnitude of the MMN amplitudes in response to the initial deviant as a likely cause for the null finding.

MMN increase for frequency deviants after duration deviants

Based on the finding of Nousak et al. (1996), we did not expect an MMN amplitude decrease when a deviant was followed by a different deviant. Surprisingly, we observed even an increase of the MMN amplitude when frequency deviants followed duration deviants (Table 2, Fig. 3, second row left). At first glance, this finding was surprising. However, when analyzing the standard tones following deviants, we found that standards after isolated duration deviants elicited a small, highly significant MMN, whereas standards after isolated frequency deviants elicited a negligibly small MMN (data not shown). Thus, the likely explanation for the increased MMN amplitude to frequency deviants after duration deviants is that such deviants represent a kind of double deviant (deviating in both frequency and duration), further supporting the set hypothesis of Nousak et al. (1996) and Deacon et al. (2000), according to which sound deviances are processed independently across different sound features.

Study limitations

The study has some limitations which need to be taken into account. First of all, the order of the two experiments was not balanced, as it usually should, because Experiment 2 was designed after Experiment 1. Any fixed order of experiments within the same individuals might result in some unwanted sequence effects, when comparing these experiments. The direct comparison of the two experiments did, however, not show any differential effects for identical repetitions. Secondly, our electrode montage did not include the tip of the nose as an additional reference channel. This reference would have allowed analyzing the MMN at the vertex and mastoids separately. However, previous studies suggested that MMN repetition effects do not vary between vertex and mastoids electrodes (Deacon et al. 2000; Müller et al. 2005a). Thirdly, the difference potentials used for the quantification of the MMN and P3a amplitudes also contained N1-related activity (Figs. 2, 3). Due to time limitations, we did not use additional control conditions which would potentially allow a better separation of N1 and MMN-related activity (e.g., Jacobsen and Schröger 2001, 2003). We believe that the lack of such control conditions had no major impact on the findings as the statistical comparison, as conducted in our study, did not depend on the ERP response to standards (the ERP responses to standards were subtracted from the ERPs to the initial deviant, as well as from the ERPs to the repeated deviant). Moreover, the N1 could be clearly identified in the ERPs to standards and the N1 peak was temporally separated by more than 60 ms from the MMN peaks to both duration and frequency deviants (see also Supplementary material). Finally, the study does not allow assessing the impact of cognitive load on the findings. In a three-tone oddball experiment, Comerchero and Polich (1999) showed larger P3a amplitudes to nontargets when target identification within the same modality was difficult (see also Hagen et al. 2006; Sawaki and Katayama

2006). In contrast, Schubert et al. (1998) reported that the auditory P3a did not differ between two concurrent motor tasks, which varied in difficulty. These studies did not contain repeated nontargets. Thus, further research is warranted to reveal under which conditions cognitive load modulates the P3a amplitude to deviants and P3a repetitions effects.

Conclusion

The P3a is strongly diminished when two identical deviants are presented in a row, whereas no such P3a attenuation is observed when different deviants occur in succession. This suggests that attention switch systems operate independently across different sound features, similar as previously reported for the MMN as deviance detection system (Nousak et al. 1996). The findings further suggest that an increased temporal predictability of a deviant has no impact on the P3a, as long as the kind of deviance is not predictable.

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Compliance with ethical standards

Conflict of interest None of the authors have potential conflicts of interest to be disclosed.

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