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Impact of emotional valence on mismatch negativity in the course of cortical face processing

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ABSTRACT

Various aspects of cortical face processing have been studied by assessing event related potentials (ERP). It has been described in the literature that mismatch negativity (MMN), a well-studied ERP, is not only modulated by sensory features but also emotional valence. However, the exact impact of emotion on the temporo-spatial profile of visual MMN during face processing remains inconsistent. By employing a sequential oddball paradigm using both neutral and emotional deviants, we were able to differentiate two distinct vMMN subcomponents. While an early subcomponent at 150–250 ms is elicited by emotional salient facial stimuli, the later subcomponent at 250–400 ms seems to reflect the detection of regularity violations in facial recognition per se, unaffected by emotional salience. Our results suggest that emotional valence is encoded in vMMN signal strength at an early stage of facial processing. Furthermore, we assume that of facial processing consists of temporo-spatially distinct, partially overlapping levels concerning different facial aspects.

1. Introduction

Cortical face processing involves different brain regions encoding different inputs referring to face perception and recognition (Calder and Young, 2005). Beyond identification of the anatomical network, the temporal dynamics of face processing have been investigated in numerous studies by assessing event related potentials (ERP) components that are associated to certain aspects of face processing (Olivares et al., 2015).

Mismatch negativity (MMN), a well-studied ERP, occurs when a presented stimulus is unexpected and thus violates an established pattern of previous stimuli. It is computed by subtracting the ERP to the standard stimulus from that to the deviant stimulus. Although long-standing and robust evidence suggests that MMN is mainly driven by automatic detection of change in a series of sensory stimuli (deviance detection, Näätänen et al. (2007)), MMN is now increasingly interpreted as an electrocortical representation of prediction error (Garrido et al., 2009; Hofmann-Shen et al., 2020; Wacongne et al., 2012).

While most studies have focused on the auditory MMN (for a review, see Näätänen et al. (2007)), MMN can also be found in the visual modality (vMMN). vMMN modulation in basic sensory features such as color, line orientation or spatial frequency has been widely studied and is still subject to ongoing research (Astikainen et al., 2008; Czigler and Pato, 2009; Czigler and Sulykos, 2010; Czigler et al., 2006; Kimura et al., 2006; Male et al., 2020; Stefanics et al., 2011, 2014; Sulykos and Czigler, 2011). While Susac et al. (2004) were the first ones to study the effect of facial expression on vMMN, Zhao and Li (2006) were able to compute a vMMN by presenting emotionally salient faces as deviants to an established neutral face in an oddball paradigm. Thus, vMMN generated by change of facial expression has been named expression mismatch negativity (EMMN).

An increasing number of studies have since turned their attention to the investigation of EMMN (e. g. Astikainen et al., 2013; Astikainen and Hietanen, 2009; Chang et al., 2010; Gayle et al., 2012; Kimura et al., 2012; Kovarski et al., 2021; Kovarski et al., 2017; Kreegipuu et al., 2013; Kuehne et al., 2019; Li et al., 2018; Li et al., 2012; Liu et al., 2015; Liu et al., 2016; Soshi et al., 2015; Stefanics et al., 2012; Susac et al., 2010; Vogel et al., 2015). A large number of different approaches, varying in

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underlying paradigm, number of presented emotions or identities, and other factors, has led to an equal number of different results, with EMMN components found in a wide latency range between 100 and 520 ms (see Kovarski et al. (2017) for an overview).

In most studies focusing on EMMN, a neutral standard was compared to one or two emotional deviants or two emotions with each other (Astikainen et al., 2013; Astikainen and Hietanen, 2009; Kimura et al., 2012; Liu et al., 2016; Stefanics et al., 2012; Zhao and Li, 2006), leaving room for doubt whether the observed vMMN were evoked by an actual change in facial expression or simply by differences in appearance between stimuli per se ("deviance detection"). Recently, some studies have compared both an emotional and neutral deviant to a neutral standard (Kovarski et al., 2017, 2021; Vogel et al., 2015, 2018), but to our knowledge, only one study (Gayle et al., 2012) has examined more than one emotional deviant and a neutral deviant in the same paradigm; however, differences of low-level stimulus features could not be ruled out.

While most studies relied on oddball paradigms in MMN research, some studies additionally used an equiprobable paradigm to control for low-level-differences and repetition suppression effects post-hoc (Astikainen et al., 2013; Kovarski et al., 2017, 2021; Li et al., 2012). In an effort to directly minimize confounders such as repetition suppression effects, we employed a sequential oddball paradigm, which has been successfully used in previous studies by our group and other groups (Ells et al., 2018; Hofmann-Shen et al., 2020; Salisbury et al., 2018; Vogel et al., 2015, 2018; Wacongne et al., 2012). The sequence oddball paradigm consists of a standard sequence, a neutral male face followed by a neutral female face, interrupted by sequences where the second face stimulus deviates in either identity or emotion. This way, the standard sequence already contains a deviant second stimulus and will thus evoke low-level deviance detection signals, which are then subtracted from our experimental conditions to calculate the MMN components. Moreover, we employed different emotional valences along with a neutral sequence deviant.

By applying the sequential oddball paradigm, we aimed to assess how visual MMN is modulated by emotional valence in the course of cortical face processing. We hypothesized that the impact of emotional valence, among other facial characteristics, on MMN might be reflected in temporo-spatially differentiable vMMN-subcomponents that are to be decomposed in our study.

2. Methods

2.1. Participants

Twenty healthy participants (15 female, 5 male) aged 19 to 32 (24.3 ± 3.4) were tested in this study. All participants were right-handed, the laterality index based on the Edinburgh Handedness Inventory (Oldfield, 1971) was 87.52 ± 14.31 and had normal or corrected-to-normal vision. Mean education time (years) was 17 ± 3.03, estimated verbal IQ was 111.94 ± 12.20 (Lehrl, 1999), non-verbal IQ was 118.45 ± 9.01 (Horn, 1983).

No participant had any history of psychiatric or neurological conditions. Prior to testing, every participant filled out a standard written consent form and completed a battery of questionnaires. Each participant received an expense allowance of 20€. The study was approved by the ethics committee of the Charité University of Medicine Berlin and was conducted in accordance with the Declaration of Helsinki and its amendments. All participants were included in the final analysis.

2.2. Procedure

Participants were seated 100 cm in front of a 22″ widescreen monitor in a dimly lit, electrically shielded room, and a headrest was used to minimize head movement during the experiment. Participants were given an auditory task to minimize attentional effects in processing of the stimuli. As in the preceding study (Vogel et al., 2015), we used the German version of the Danish tale "Garden of Paradise" by Hans Christian Andersen, which was retrieved from the online audiobook database librivox.org. Participants were asked 10 multiple-choice questions about the tale after the experiment. An error rate of 50% or more led to exclusion of the study. Participants who already knew the tale were also excluded. To ensure that participants stayed focused on the screen, they were given an auxiliary visual task. Participants were instructed to press the left mouse button whenever they saw a salient red star, which was added to 10% of the pictures as behavioral control trials. An accuracy below 80% led to exclusion from the study. The faces database was provided by the Max-Planck Institute of Biological Cybernetics in Tübingen, Germany (Blanz and Vetter, 1999; Troje and Bulthoff, 1996).

2.3. Paradigm

The EEG paradigm consisted of a learning phase and a testing phase, variations of the classic oddball paradigm. In the learning phase, a standard condition consisting of two pictures – a neutral male followed by a neutral female – was established in 40 repetitions, with a stimulus onset asynchrony of 600 ms and a stimulus presentation time of 150 ms. In the testing phase, each consisting of 4 blocks with 100 trials of different pseudo-randomized trial order, the standard condition (neutral male – neutral female) was shown 70% of the time. There were three deviant conditions: Sequence deviant (neutral male – neutral male), fearful deviant (neutral male – fearful female) and happy deviant (neutral male – happy female). Each of the deviant conditions was shown in 10% of the time. Behavioral control trials (10% of all trials) were evenly distributed across blocks (see also Fig. 1). After each block, the participants were given a short break. The experiment lasted for approximately 45 min.

2.4. EEG acquisition and analysis

EEG data were acquired using WaveGuard electrode caps with 64 Ag/Ag–Cl electrodes, ASA software and a DC amplifier (ANT Neurosystems, Enschede, The Netherlands) with a sampling rate of 512 Hz. During recording, impedances were kept below 5 kΩ, channels were referenced to Cz, and AFz served as ground.

Data were analyzed using BrainVision Analyzer 2 (Brain Products, Munich, Germany). First, EEG signals were filtered using 0.5 Hz high-pass and 20 Hz low-pass filters at 24dB/octave each. Signals were then re-referenced to common average and down-sampled to 500 Hz. Independent component analysis (Jung et al., 2000) was used for ocular artifact correction. Remaining artifacts were defined with an amplitude criterion of 80 μV (every channel) and tagged for later removal. EEG data were then segmented according to experimental conditions and artifact-contaminated segments were removed. After baseline correction, ERPs were averaged for every condition.

We then calculated difference waves by subtracting the ERP evoked by the standard condition from the ERP evoked by each deviant condition, thus creating vMMN components elicited by the different deviant conditions: vMMN elicited by sequence deviants, vMMN elicited by fearful deviants and vMMN elicited by happy deviants. Based on own previous research (Vogel et al., 2015) and on visual inspection of butterfly plots of grand averaged difference waves as well as topographical maps, six electrodes that represent the underlying regions of interest were selected for further analysis: P7, P07, P09 (left hemisphere) and P8, P08, P010 (right hemisphere; see also Fig. 2a/b). Visual inspection indicated two distinct vMMN peaks, so that two intervals for peak detection were chosen: 150 to 250 ms for the early peak and 250 to 400 ms for the late peak. Peak information (voltage minima in the selected latency interval) on voltage and latency were exported. Again, based on visual inspection, we also exported voltage and latency information for the N170 component in the un-subtracted ERPs choosing the same

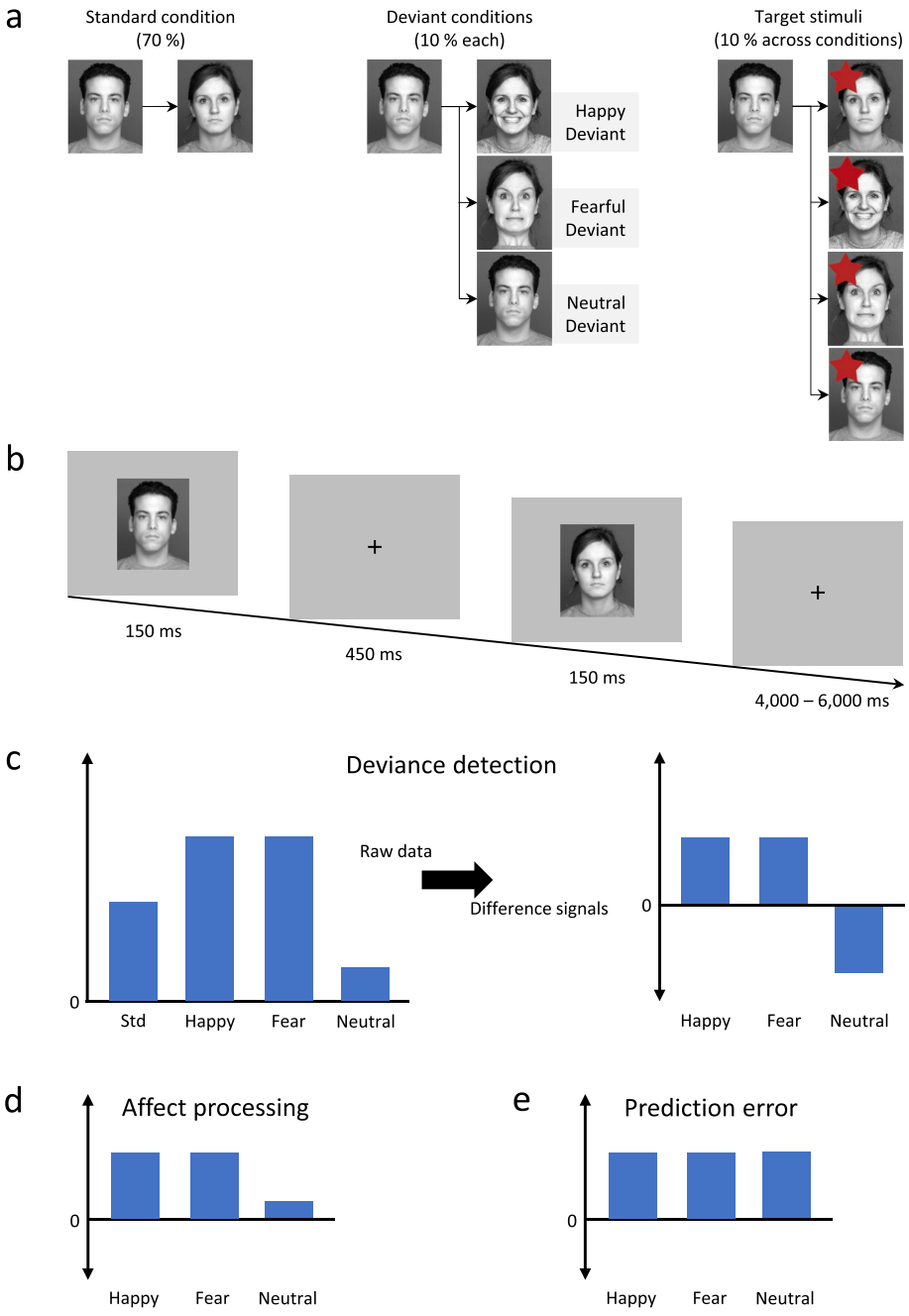

Fig. 1. Stimulus sequences, paradigm structure, and principal hypotheses. *(a)* The experiment consisted of repeated presentations of stimulus pairs. All stimuli were still pictures of a male and a female face. After a learning phase with 40 presentations of the standard male-female (neutral) sequence, the experimental phase consisted of 400 trials including the standard sequence (probability .7 = 280 trials) and three deviant sequences male-female (happy), male-female (fearful), and male-male (probability .1 = 40 trials each). Arithmetically, every tenth trial served as a behavioral control trial (N = 40); control trials were distributed across experimental conditions proportionate to their overall probability. *(b)* Task schematic with a presentation time of 150 ms for each stimulus, an interstimulus interval of 450 ms, and a jittered intertrial interval of 4000 to 6000 ms. *(c)* Detection of physical stimulus deviance was hypothesized to occur in response to stimulus 2 in all sequences consisting of different faces, i.e. standard sequence, happy deviant, and fearful deviant. After subtracting ERP responses (deviant minus standard), deviance detection signals should be present in happy and in fearful deviant conditions, and an opposite directionality should be found in response to the neutral deviant condition. *(d)* Correspondingly, processing of pictorial facial affects should be found in emotionally deviant conditions only, whereas neuronal activity in response to the neutral deviant condition should be close to zero. *(e)* Violations of the established prediction male-female (neutral) were hypothesized to occur in all deviant sequences with comparable signal strength.

electrodes and time window as for the early peak. In order to confirm the existence of a significant negativity in the deviant conditions compared to the standard condition, mean amplitudes of the averaged, un-subtracted ERPs pooled across the selected electrodes in both time frames were extracted for further analysis.

2.5. Statistical analysis

SPSS 28 (produced by IBM Corp., Armonk NY) was used for statistical analyses. Alpha was set at $P < 0.05$ for all tests. In a first step, in order to verify the existence of significant negativities in the time frames of interest, mean amplitude values for all experimental conditions (standard, sequence deviant, fearful deviant, happy deviant) were analyzed in a rmANOVA employing a 4-level design, contrast analysis, and corrections based on the Bonferroni method. Formal confirmation of temporal independency between ERP components was done with contrast analysis of peak latencies. Furthermore, we then compared observed amplitudes of each deviant condition to zero using one-sample t-tests. Afterwards, rmANOVAs using the within-subject factors "Condition" and "Hemisphere" were computed for each of the two vMMN components examining peak amplitudes. For the early component, based on the findings of mean amplitude analysis, a 2 × 2 design (happy deviant, fearful deviant) was employed, while for the late peak, we used a 3 × 2 design (sequence deviant, fearful deviant, happy deviant). Significant main effects were post-hoc analyzed by t-Tests. Post-hoc tests were corrected based on the Bonferroni method. Effect sizes for ANOVA effects were reported as partial eta squared, effect sizes for pair-wise contrasts were calculated as Cohen's $d = |(M_1 - M_2)|/SD_{pooled}$.

2.6. Data availability statement

Raw data were generated at the Department of Psychiatry, Charité

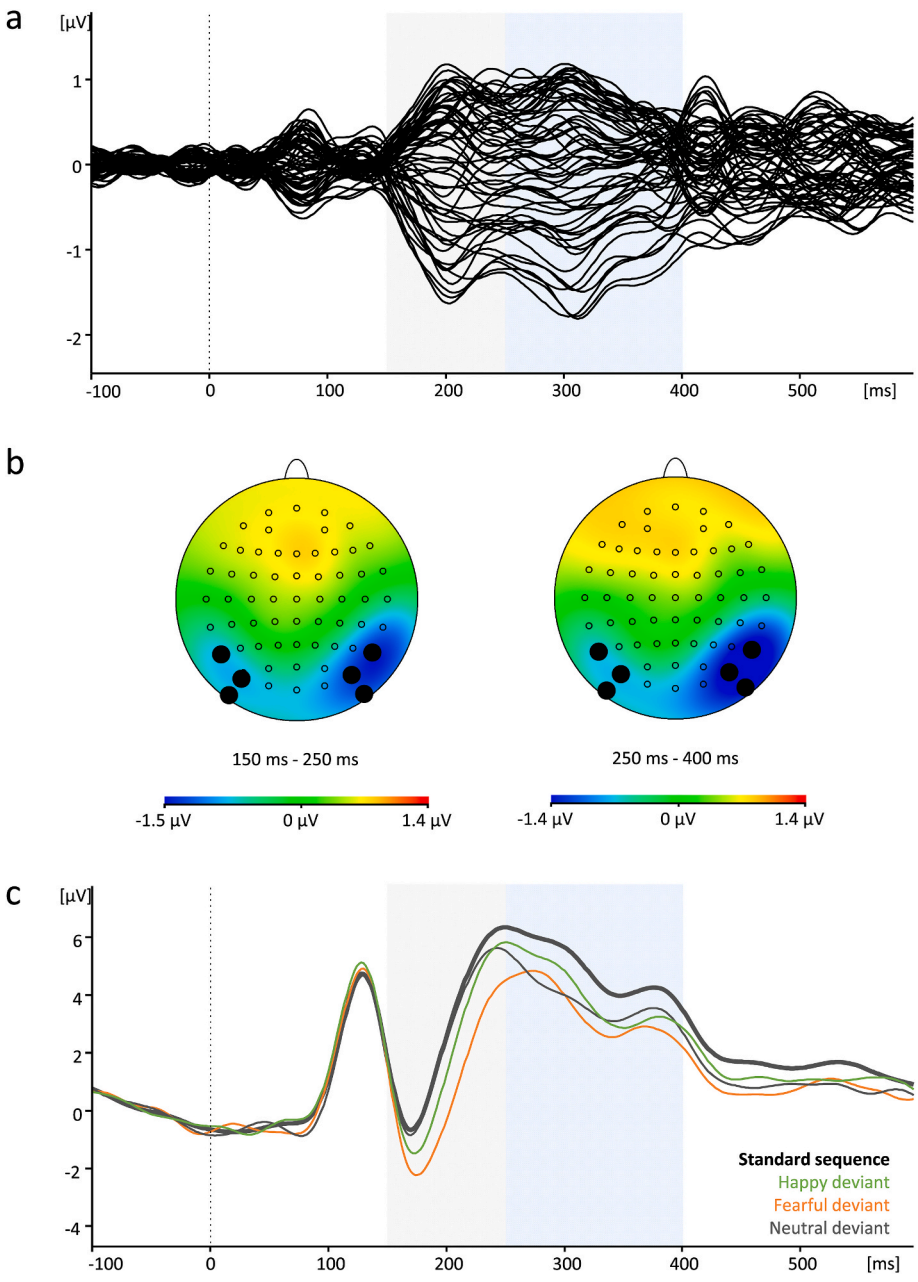

Fig. 2. EEG data mining. *(a)* Butterfly plot averaged across all difference waves, i.e. deviant minus standard. Two distinct signals were identified at 150–250 ms and 250–400 ms, respectively, which served as early and late time frames for further analyses. *(b)* Corresponding topographical maps showing maximal negativities over posterior electrodes P7, P9, and PO9 (left) as well as P8, P10, and PO10 (right hemisphere), which then served as regions of interest. *(c)* Grand averaged ERP responses stratified by condition and pooled across electrodes. Between 150 and 400 ms, significant amplitude negativations in response to deviant sequences (thin lines) as compared to the standard sequence (thick line) suggest clear vMMN activities that were computed separately for the previously identified early and late frames.

University Medicine Berlin. EEG raw data (.eeg,.vhdr,.vmrk) as well as exported peak and mean amplitude properties (voltage, latency;.txt) are available from the corresponding author on request.

3. Results

3.1. N170 effects

Repeated measures ANOVA of the N170 component revealed significant main effects of "Condition" ($F_{3,\ 57} = 7649$; $P < 0.001$; $\eta^2 = 0.287$). Post hoc t-tests showed that N170 evoked in the standard condition (– 1.52 ± 3.09 μV) was significantly smaller than when evoked in the fearful (– 3.22 ± 4.03 μV; $T_{(19)} = 4.939$; $P < 0.001$) or happy condition (– 2.47 ± 4.34 μV; $T_{(19)} = 3.073$; $P = 0.036$), but there was no significant difference compared to the neutral condition (– 1.94 ± 3.50 μV; $T_{(19)} = 1.514$; $P = 0.876$). The fearful condition evoked a N170 significantly different compared to the neutral ($T_{(19)} = – 2.958$; $P = 0.048$) but not to the happy condition ($T_{(19)} = – 1.555$; $P = 0.816$). The N170 evoked by the happy condition did not differ significantly from the N170 evoked by the neutral condition ($T_{(19)} = 1.457$; $P = 0.966$). We also found a main effect for "Hemisphere" ($F_{1,\ 19} = 14.934$; $P = 0.001$; $\eta^2 = 0.440$) which was driven by significantly more negative N170 evoked in the right hemisphere (– 3.45 ± 4.37 μV) than in the left hemisphere (– 1.12 ± 3.71 μV; $T_{(19)} = – 3.864$; $P = 0.001$). We observed no significant interaction.

3.2. MMN effects

We first analyzed mean amplitudes of all experimental conditions in our time frames of interest to confirm the presence of significant negativities in our deviant conditions. The first time frame (150–250 ms) revealed a significant main effect of "Condition" ($F_{(2.14,\ 40.60)} = 16.952$; $P < 0.001$; $\eta^2 = 0.472$), where the mean amplitude of the standard condition (2.71 ± 3.06 μV) was significantly more positive than the mean amplitude of the fearful (0.63 ± 3.15 μV; $F_{(1,\ 19)} = 47.740$; $P < 0.001$) and the happy deviant (1.85 ± 3.48 μV; $F_{(1,\ 19)} = 10.525$; $P =$

0.012), but not the sequence deviant (2.44 ± 2.85 μV; $F_{(1, 19)} = 1.721$; P = 0.615). This justified analyzing difference wave peak amplitudes for the fearful and happy deviants only. Subsequent one-sample t-tests of the observed peaks of the difference waves in the deviant conditions fearful and happy in this time window showed significant negativities compared to zero (fearful: – 3.50 ± 1.78 μV; $T_{(19)} = -8.791$; P = < 0.001; happy: – 1.89 ± 1.52; $T_{(19)} = -5.540$; P = < 0.001). At this point, a contrast analysis showed that N170 (176.88 ± 13.73 ms) peaked significantly earlier than the early vMMN component (200.34 ± 9.86 ms; $F_{(1, 19)} = 27.798$; P < 0.001). Next, the second time frame (250–400 ms) also showed a significant main effect of "Condition" ($F_{(3, 57)} = 7.856$; P < 0.001; $\eta^2 = 0.293$), where the mean amplitude of the standard condition (4.94 ± 2.34 μV) was significantly more positive than mean amplitudes of sequence (3.82 ± 2.19 μV; $F_{(1, 19)} = 22.611$; P < 0.001), fearful (3.46 ± 2.63 μV; $F_{(1, 19)} = 28.886$; P < 0.001), and happy deviants (4.06 ± 2.91 μV; $F_{(1, 19)} = 8.054$; P = 0.033), thus enabling to compute and analyze difference waves for all three deviant conditions (see also Fig. 2c) One-sample t-tests in this time window again showed significant negativities of the difference wave peaks compares to zero for all deviant conditions (fearful: – 2.72 ± 1.64 μV; $T_{(19)} = -7.425$; P = < 0.001; happy: – 2.07 ± 1.57; $T_{(19)} = -5.880$; P = < 0.001; sequence: – 2.48 ± 1.26 μV; $T_{(19)} = -8.802$; P = < 0.001).

Repeated measures ANOVA of the early MMN component showed a significant main effect of "Condition" ($F_{(1, 19)} = 9.236$; P = 0.007; $\eta^2 = 0.327$), which was driven by a significantly larger vMMN elicited in the fearful condition (– 3.50 ± 1.78 μV) than in the happy condition (– 1.89 ± 1.52 μV; $T_{(19)} = -3.039$; P = 0.007) with an effect size of d = 0.973, corresponding to a large effect size (see also Fig. 3a). There was also a significant main effect of "Hemisphere" ($F_{(1, 19)} = 5.451$ P = 0.031; $\eta^2 = 0.223$), where the vMMN elicited in the right hemisphere (– 3.04 ± 1.38 μV) was significantly larger than in the left hemisphere (– 2.34 ± 1.29 μV; $T_{(19)} = -2.335$; P = 0.031). There was no significant interaction.

Repeated measures ANOVA of the late MMN component revealed a significant main effect of "Hemisphere" ($F_{(1, 19)} = 29.093$; P < 0.001; $\eta^2 = 0.605$), that was driven by a significantly larger vMMN evoked in the right hemisphere (2.92 ± 1.28 μV) than in the left hemisphere (1.93 ± 1.01 μV; $T_{(19)} = -5.394$; P < 0.001). There was no other significant main effect or interaction.

Contrast analysis between MMN components showed a significant peak latency difference between early (200.43 ± 9.86 ms) and late MMN (325.02 ± 14.50 ms; $F_{(1, 19)} = 718.805$; P < 0.001), thereby suggesting temporal independence.

4. Discussion

We investigated the influence of emotional valence on visual MMN. In order to assess the impact of emotional salience compared to neutral stimuli, we used two different emotional deviants and one neutral

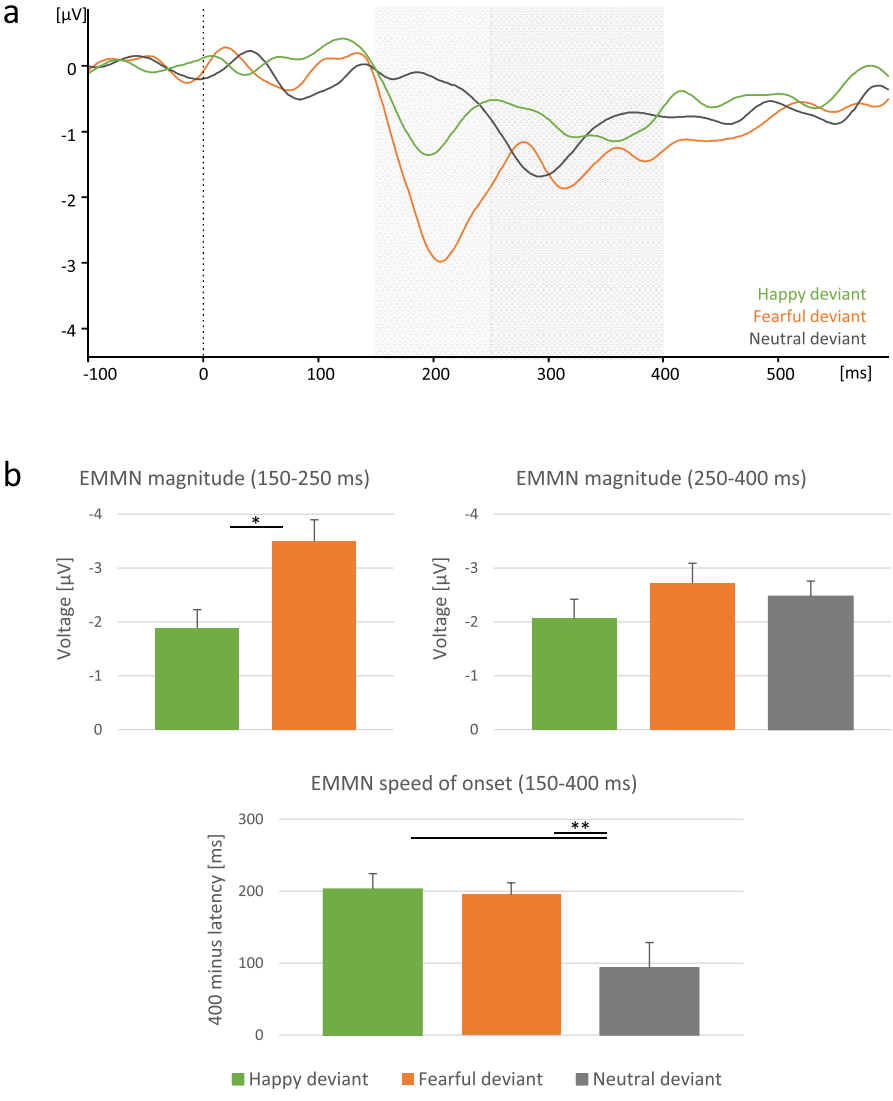

Fig. 3. vMMN responses per condition. (a) vMMN components for happy, fearful, and neutral deviants, where 0 ms corresponds to S2 onset of second stimuli. In the first time frame 150–250 ms, clear vMMN signal peaks are seen in the happy and the fearful, but not for the neutral condition. In the second time frame 250–400 ms, vMMN signal peaks are present in all deviant conditions. (b) Bar graphs of vMMN signal magnitude (i.e. voltage; negativity plotted upwards) and vMMN signal speed of onset defined as inversed latency (i.e. last observation data point at 400 ms minus latency of first peak per condition). vMMN magnitudes at 250–400 ms conform to the signal pattern expected in response to rule violations in general, i.e. "cognitive" prediction error. Speed of onset of vMMN signals correspond to the signal pattern hypothesized in response to emotional face stimuli, i.e. "emotional" prediction error. Interestingly, emotional valence, i.e. happy vs. fearful, seems to be differentially coded by vMMN signal magnitudes at 150–250 ms. Error bars represent SEM (magnitude) or SD (speed of onset), respectively. *, p < 0.01; **, p < 0.001.

deviant. By employing a sequential oddball paradigm, we were able to establish a firm distinction between an early and a late MMN subcomponent. An early vMMN signal, peaking around 200 ms, was found only for emotional face expressions, whereas a later vMMN signal peaking around 310 ms was elicited by both emotionally salient and neutral faces. This dissociation provides evidence for distinct mechanisms underlying emotional and non-emotional facial processing.

We analyzed the N170 response in order to rule out temporal overlaps with the vMMN component. We found that both fearful and happy faces elicited a larger N170 compared to neutral faces. Our finding is consistent with various previous studies (Astikainen and Hietanen, 2009; Li et al., 2012; Zhao and Li, 2006) describing an emotional modulation of N170. Astikainen et al. (2013) assumed that the early vMMN-subcomponent might be identical to the N170 response, based on similar latencies and scalp distribution of both components, which was also found in other studies (Chang et al., 2010; Stefanics et al., 2012; Zhao and Li, 2006). On the other hand, Kreegipuu et al. (2013) observed a posterior negativity in a similar time frame that lasted too long to be explained exclusively by sensory activity (i.e. N170) and thus argued in favor of two different cortical signatures. Our results show significantly different latencies between the early vMMN response and the N170 component, thus supporting the results of Kreegipuu et al. (2013).

Although modulations of visual mismatch negativity elicited by face expression have been replicated in most studies (Astikainen and Hietanen, 2009; Kimura et al., 2012; Kovarski et al., 2017; Stefanics et al., 2012; Zhao and Li, 2006), the influence of emotional expressions on spatio-temporal characteristics of facial MMN is subject to ongoing discussions. It has been proposed that inconsistencies between studies might result from differences in stimuli presentation and paradigm design (Kovarski et al., 2017). Our study used a sequential oddball paradigm to help distinguish between the processing of facial emotions and facial recognition per se, while at the same time eliminating the influence of low-level features.

We differentiated two spatio-temporally distinct vMMN subcomponents. The early vMMN component at 150–250 ms was evoked by emotionally salient but not neutral face deviants, which strongly suggests that facial emotion is selectively processed at this stage, which largely confirms an earlier finding by Astikainen and Hietanen (2009). While it can be assumed that the early vMMN component reflexes processing of facial emotion in general, it is not to clarify whether the early vMMN component is also influenced by deviance detection of emotional salient faces. In order to target this question, an extended sequential paradigm with control conditions in terms of sequentially presented emotional salient faces is needed.

Regarding emotional valence, fearful facial expressions following neutral faces elicited larger early vMMN amplitudes than did happy facial expressions, which is in line with previous studies (Eimer and Holmes, 2007; Gayle et al., 2012; Vuilleumier and Pourtois, 2007). This has been coined “negativity bias”, where unexpected negative emotions are processed with a more pronounced amplitude compared to positive emotions or neutral faces (Stefanics et al., 2012). This has been shown mostly for fearful faces (Ashley et al., 2004; Batty and Taylor, 2003; Leppanen et al., 2007; Pourtois et al., 2005) and has been reproduced in more recent EMMN-studies for various negative emotions (Kovarski et al., 2017, 2021; Kuehne et al., 2019). The importance of facilitated detection of possibly threatening emotions in faces regardless of attention is especially meaningful in an evolutionary context. While vMMN is the correlate of automatic change-detection of unattended stimuli, the magnitude of the prediction error response is related to discrimination ability and consequent behavioral measures, and thus vMMN could be understood as a trigger for attentional shift (Stefanics et al., 2014). Similar mechanisms have been shown in an fMRI study, demonstrating that the amygdala, which is critical in processing fearful expressions, showed no reduced responses to fearful faces under unattended conditions (Anderson et al., 2003).

The late vMMN subcomponent at 250–400 ms was elicited by both emotionally salient and neutral deviant faces. This finding is principally in line with other EMMN studies, however, it has been inconsistently discussed as reflecting either an emotion-specific process or a reflection of mere regularity violation, without reflecting emotional content (Astikainen and Hietanen, 2009; Gayle et al., 2012; Kovarski et al., 2017, 2021; Susac et al., 2010). We found no significant differences in amplitude between neutral and emotional deviants in this late component, thereby suggesting that this component reflects the detection of regularity violations in facial recognition per se, unaffected by emotional salience. The principal distinction between two independent processes of facial expression and facial recognition is supported by previous EEG and MEG studies (Astikainen and Hietanen, 2009; Johnston et al., 2017; Kovarski et al., 2017, 2021; Robinson et al., 2020).

Both VMMN-subcomponents showed a parieto-occipital distribution and a strong right-hemispheric predominance in amplitudes. The right-hemispheric dominance in vMMN is in good accordance with the right hemisphere hypothesis of emotional processing (Adolphs et al., 1996; Alves et al., 2009) and has been reproduced in many studies (Gayle et al., 2012; Li et al., 2012; Vogel et al., 2015).

A main limitation of the present study is, as already mentioned above, the lack of emotional salient control conditions in our paradigm (emotional salient, identical faces in the standard vs. emotional salient, different faces in the deviant condition). Thus, it can only be stated that the detected early vMMN subcomponent is elicited by emotional salient faces, while the effect of detection of changing facial emotions on vMMN could not be investigated. However, our results suggest a varying modulatory impact of different emotions on vMMN, since fearful faces elicited vMMN with higher amplitudes compared to happy faces. Further, it has to be acknowledged that our paradigm allows for minimizing low-level biases of sensory processing, on the other hand, repetition suppression and prediction error effects are difficult to disentangle here. The sequence deviant consists of the unexpected presentation of the same stimulus, whereas the emotional deviant consists of the unexpected presentation of a different stimulus. Both conditions, however, evoked a clear-cut late mismatch response, which indicates sufficient recruitment of neuronal resources in both conditions. Moreover, while we used an auditory task was used to engage the attention of the participants, we also used a visual task to ensure that participants focused on the screen, which may lead to undesired attention effects. We tried to counterbalance this by distributing target stimuli evenly across all conditions.

In conclusion, our findings allow for differentiating between distinct stages within facial processing. While the N170 and the directly following early vMMN component are modulated by emotionally salient sensory inputs, the late vMMN component is more linked to facial recognition in general. Thus, facial processing consists of temporo-spatially distinct, partially overlapping levels concerning different facial aspects.

CRediT authorship contribution statement

Maximilian Kaffes: Conceptualization, Methodology, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Lea Rabe:** Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft. **Armin Rudolph:** Formal analysis, Data curation, Writing – original draft. **Johannes Rentzsch:** Data curation, Writing – original draft. **Andres H. Neuhaus:** Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing, Visualization, Project administration, Resources. **Christina Hofmann-Shen:** Funding acquisition, Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial

interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crneur.2023.100078.

References

Adolphs, R., et al., 1996. Cortical systems for the recognition of emotion in facial expressions. J. Neurosci. 16, 7678–7687.
Alves, N.T., et al., 2009. Patterns of brain asymmetry in the perception of positive and negative facial expressions. Laterality 14, 256–272. https://doi.org/10.1080/13576500802362927.
Anderson, A.K., et al., 2003. Neural correlates of the automatic processing of threat facial signals. J. Neurosci. 23, 5627–5633.
Ashley, V., et al., 2004. Time course and specificity of event-related potentials to emotional expressions. Neuroreport 15, 211–216. https://doi.org/10.1097/00001756-200401190-00041.
Astikainen, P., et al., 2013. Event-related potentials to unattended changes in facial expressions: detection of regularity violations or encoding of emotions? Front. Hum. Neurosci. 7, 557. https://doi.org/10.3389/fnhum.2013.00557.
Astikainen, P., Hietanen, J.K., 2009. Event-related potentials to task-irrelevant changes in facial expressions. Behav. Brain Funct. 5, 30. https://doi.org/10.1186/1744-9081-5-30.
Astikainen, P., et al., 2008. Visual mismatch negativity for changes in orientation–a sensory memory-dependent response. Eur. J. Neurosci. 28, 2319–2324. https://doi.org/10.1111/j.1460-9568.2008.06510.x.
Batty, M., Taylor, M.J., 2003. Early processing of the six basic facial emotional expressions. Brain Res. Cogn. Brain Res. 17, 613–620. https://doi.org/10.1016/s0926-6410(03)00174-5.
Blanz, V., Vetter, T., 1999. A morphable model for the synthesis of 3D faces. In: Proceedings of the 26th Annual Conference on Computer Graphics and Interactive Techniques. ACM Press/Addison-Wesley Publishing Co., pp. 187–194
Calder, A.J., Young, A.W., 2005. Understanding the recognition of facial identity and facial expression. Nat. Rev. Neurosci. 6, 641–651. https://doi.org/10.1038/nrn1724.
Chang, Y., et al., 2010. Dysfunction of processing task-irrelevant emotional faces in major depressive disorder patients revealed by expression-related visual MMN. Neurosci. Lett. 472, 33–37. https://doi.org/10.1016/j.neulet.2010.01.050.
Czigler, I., Pato, L., 2009. Unnoticed regularity violation elicits change-related brain activity. Biol. Psychol. 80, 339–347. https://doi.org/10.1016/j.biopsycho.2008.12.001.
Czigler, I., Sulykos, I., 2010. Visual mismatch negativity to irrelevant changes is sensitive to task-relevant changes. Neuropsychologia 48, 1277–1282. https://doi.org/10.1016/j.neuropsychologia.2009.12.029.
Czigler, I., et al., 2006. ERPs and deviance detection: visual mismatch negativity to repeated visual stimuli. Neurosci. Lett. 401, 178–182. https://doi.org/10.1016/j.neulet.2006.03.018.
Eimer, M., Holmes, A., 2007. Event-related brain potential correlates of emotional face processing. Neuropsychologia 45, 15–31. https://doi.org/10.1016/j.neuropsychologia.2006.04.022.
Ells, E.M.L., et al., 2018. Alterations of complex mismatch negativity (cMMN) elicited by a two-tone pattern paradigm in early-phase psychosis. Biol. Psychol. 135, 128–135. https://doi.org/10.1016/j.biopsycho.2018.03.010.
Garrido, M.I., et al., 2009. The mismatch negativity: a review of underlying mechanisms. Clin. Neurophysiol. 120, 453–463. https://doi.org/10.1016/j.clinph.2008.11.029.
Gayle, L.C., et al., 2012. Measuring affective reactivity in individuals with autism spectrum personality traits using the visual mismatch negativity event-related brain potential. Front. Hum. Neurosci. 6, 334. https://doi.org/10.3389/fnhum.2012.00334.
Hofmann-Shen, C., et al., 2020. Mapping adaptation, deviance detection, and prediction error in auditory processing. Neuroimage 207, 116432. https://doi.org/10.1016/j.neuroimage.2019.116432.
Horn, W., 1983. Leistungsprüfsystem: LPS. Hogrefe, Göttingen.
Johnston, P., et al., 2017. Temporal and spatial localization of prediction-error signals in the visual brain. Biol. Psychol. 125, 45–57. https://doi.org/10.1016/j.biopsycho.2017.02.004.
Jung, T.P., et al., 2000. Removing electroencephalographic artifacts by blind source separation. Psychophysiology 37, 163–178.
Kimura, M., et al., 2006. Probability-independent and -dependent ERPs reflecting visual change detection. Psychophysiology 43, 180–189. https://doi.org/10.1111/j.1469-8986.2006.00388.x.
Kimura, M., et al., 2012. Unintentional temporal context-based prediction of emotional faces: an electrophysiological study. Cerebr. Cortex 22, 1774–1785. https://doi.org/10.1093/cercor/bhr244.
Kovarski, K., et al., 2021. Emotional visual mismatch negativity: a joint investigation of social and non-social dimensions in adults with autism. Transl. Psychiatry 11, 10. https://doi.org/10.1038/s41398-020-01133-5.
Kovarski, K., et al., 2017. Facial expression related vMMN: disentangling emotional from neutral change detection. Front. Hum. Neurosci. 11, 18. https://doi.org/10.3389/fnhum.2017.00018.
Kreegipuu, K., et al., 2013. vMMN for schematic faces: automatic detection of change in emotional expression. Front. Hum. Neurosci. 7, 714. https://doi.org/10.3389/fnhum.2013.00714.
Kuehne, M., et al., 2019. Out of focus: facial feedback manipulation modulates automatic processing of unattended emotional faces. J. Cognit. Neurosci. 31, 1631–1640. https://doi.org/10.1162/jocn_a_01445.
Lehrl, S., 1999. Mehrfachwahl-Wortschatz-Intelligenztest. MWT-B. Balingen: Spitta.
Leppanen, J.M., et al., 2007. An ERP study of emotional face processing in the adult and infant brain. Child Dev. 78, 232–245. https://doi.org/10.1111/j.1467-8624.2007.00994.x.
Li, Q., et al., 2018. Female advantage in automatic change detection of facial expressions during a happy-neutral context: an ERP study. Front. Hum. Neurosci. 12, 146. https://doi.org/10.3389/fnhum.2018.00146.
Li, X., et al., 2012. Visual mismatch negativity elicited by facial expressions: new evidence from the equiprobable paradigm. Behav. Brain Funct. 8, 7. https://doi.org/10.1186/1744-9081-8-7.
Liu, T., et al., 2015. Fluid intelligence and automatic neural processes in facial expression perception: an event-related potential study. PLoS One 10, e0138199. https://doi.org/10.1371/journal.pone.0138199.
Liu, T., et al., 2016. Automatic change detection to facial expressions in adolescents: evidence from visual mismatch negativity responses. Front. Psychol. 7, 462. https://doi.org/10.3389/fpsyg.2016.00462.
Male, A.G., et al., 2020. The quest for the genuine visual mismatch negativity (vMMN): event-related potential indications of deviance detection for low-level visual features. Psychophysiology 57, e13576. https://doi.org/10.1111/psyp.13576.
Näätänen, R., et al., 2007. The mismatch negativity (MMN) in basic research of central auditory processing: a review. Clin. Neurophysiol. 118, 2544–2590. https://doi.org/10.1016/j.clinph.2007.04.026.
Oldfield, R.C., 1971. The assessment and analysis of handedness: the Edinburgh inventory. Neuropsychologia 9, 97–113.
Olivares, E.I., et al., 2015. Iglesias J, Saavedra C, Trujillo-Barreto NJ, Valdés-sosa M. Brain signals of face processing as revealed by event-related potentials. Behav. Neurol., 514361 https://doi.org/10.1155/2015/514361, 2015.
Pourtois, G., et al., 2005. Enhanced extrastriate visual response to bandpass spatial frequency filtered fearful faces: time course and topographic evoked-potentials mapping. Hum. Brain Mapp. 26, 65–79. https://doi.org/10.1002/hbm.20130.
Robinson, J.E., et al., 2020. Prediction-error signals to violated expectations about person identity and head orientation are doubly-dissociated across dorsal and ventral visual stream regions. Neuroimage 206, 116325. https://doi.org/10.1016/j.neuroimage.2019.116325.
Salisbury, D.F., et al., 2018. Complex mismatch negativity to tone pair deviants in long-term schizophrenia and in the first-episode schizophrenia spectrum. Schizophr. Res. 191, 18–24. https://doi.org/10.1016/j.schres.2017.04.044.
Soshi, T., et al., 2015. Neurophysiological modulation of rapid emotional face processing is associated with impulsivity traits. BMC Neurosci. 16, 87. https://doi.org/10.1186/s12868-015-0223-x.
Stefanics, G., et al., 2014. Visual mismatch negativity (vMMN): a prediction error signal in the visual modality. Front. Hum. Neurosci. 8, 1074. https://doi.org/10.3389/fnhum.2014.01074.
Stefanics, G., et al., 2012. Processing of unattended facial emotions: a visual mismatch negativity study. Neuroimage 59, 3042–3049. https://doi.org/10.1016/j.neuroimage.2011.10.041.
Stefanics, G., et al., 2011. Visual mismatch negativity reveals automatic detection of sequential regularity violation. Front. Hum. Neurosci. 5, 46. https://doi.org/10.3389/fnhum.2011.00046.
Sulykos, I., Czigler, I., 2011. One plus one is less than two: visual features elicit non-additive mismatch-related brain activity. Brain Res. 1398, 64–71. https://doi.org/10.1016/j.brainres.2011.05.009.
Susac, A., et al., 2010. Early cortical responses are sensitive to changes in face stimuli. Brain Res. 1346, 155–164. https://doi.org/10.1016/j.brainres.2010.05.049.
Susac, A., et al., 2004. Neurodynamic studies on emotional and inverted faces in an oddball paradigm. Brain Topogr. 16, 265–268. https://doi.org/10.1023/b:brat.0000032863.39907.cb.
Troje, N.F., Bulthoff, H.H., 1996. Face recognition under varying poses: the role of texture and shape. Vis. Res. 36, 1761–1771. https://doi.org/10.1016/0042-6989(95)00230-8.
Vogel, B.O., et al., 2015. Emotional context facilitates cortical prediction error responses. Hum. Brain Mapp. 36, 3641–3652. https://doi.org/10.1002/hbm.22868.
Vogel, B.O., et al., 2018. Emotional context restores cortical prediction error responses in schizophrenia. Schizophr. Res. 197, 434–440. https://doi.org/10.1016/j.schres.2018.02.030.

Vuilleumier, P., Pourtois, G., 2007. Distributed and interactive brain mechanisms during emotion face perception: evidence from functional neuroimaging. Neuropsychologia 45, 174–194. https://doi.org/10.1016/j.neuropsychologia.2006.06.003.

Wacongne, C., et al., 2012. A neuronal model of predictive coding accounting for the mismatch negativity. J. Neurosci. 32, 3665–3678. https://doi.org/10.1523/JNEUROSCI.5003-11.2012.

Zhao, L., Li, J., 2006. Visual mismatch negativity elicited by facial expressions under non-attentional condition. Neurosci. Lett. 410, 126–131. https://doi.org/10.1016/j.neulet.2006.09.081.