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Research Report

Mediofrontal negativities in the absence of responding

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Abstract

The feedback-related negativity (FRN) is an event-related brain potential component that is elicited by feedback stimuli indicating unfavorable outcomes. Until recently, the FRN has been studied primarily using experimental paradigms in which outcomes appeared to be contingent upon the participants' behavior. The present study further addressed the question whether an FRN can be elicited by outcomes that are not contingent on any preceding choice or action. Participants took part in a simple slot-machine task in which they experienced monetary gains and losses in the absence of responses. In addition, they performed a time estimation task often used to study the FRN and a flanker task known to elicit the error-related negativity. Outcomes in the slot-machine task elicited an FRN-like mediofrontal negativity whose amplitude correlated with the amplitude of the FRN associated with negative feedback in the time estimation task. However, the mediofrontal negativity was observed both for (unfavorable) outcomes that averted a gain and for (favorable) outcomes that averted a loss of money. The results are discussed in the framework of current conceptions of the FRN and related electrophysiological components.
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1. Introduction

In recent years, a variety of event-related potential (ERP) studies in humans have shown increased medial frontal cortex activity in situations calling for cognitive control. A major part of this research has been dedicated to the performance monitoring aspect of cognitive control (see [28] for a recent review). This research has identified a number of ERP components that are differentially sensitive to positive and negative feedback [33]. For example, Miltner, Brown and Coles [20] reported a negative brain potential, peaking about 250 ms following the presentation of performance feedback in a time estimation task. This feedback-related negativity[1] (FRN) was more pronounced for negative feedback, indicating that the participant's time estimate was incorrect. Equivalent dipole source analysis indicated that the frontocentral scalp distribution of this negative modulation was consistent with a generator in or near the anterior cingulate cortex. Various other studies have reported a similar differential ERP response to positive and negative performance feedback, and to financial rewards and punishments (e.g., in gambling paradigms), with unfavorable outcomes typically resulting in an increased negativity (e.g., [7,16,23], for a review see [22]).

The characteristics of the feedback-related negativity correspond in many respects to another negative component described earlier in the performance monitoring

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[1] Because of the similarity between the ERN and FRN, various authors have referred to the FRN as the "feedback ERN".

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literature: the error negativity [6] or error-related negativity [9]. The error-related negativity (ERN) is observed after incorrect responses in choice reaction time tasks, peaking about 80 ms following the erroneous response, and has a frontocentral scalp distribution similar to that of the FRN. In addition, dipole source modeling studies have suggested a neural source located in medial frontal regions, most probably the anterior cingulate cortex (e.g., [3,14]). The close resemblance of the observed negativity following an erroneous response and that following negative feedback led Miltner et al. [20] to hypothesize that the two components may reflect the activity of a generic error detection system in the brain.

Recently, Holroyd and Coles [13] (see also, [18]) have extended Miltner et al.'s [20] hypothesis regarding the cognitive and neural system underlying mediofrontal negativities following errors and negative feedback. They proposed that medial frontal negativities may reflect a negative reward prediction error signal that is elicited when the monitoring system first detects that the consequences of an action are worse than expected. This reward prediction error signal is coded by the mesencephalic dopamine system and projected to the anterior cingulate cortex, where it elicits the ERN/FRN and where it is used to negatively reinforce inappropriate behaviors. Furthermore, Holroyd and Coles proposed that the monitoring system can base its reward predictions on internal information (e.g., erroneous responses, eliciting an ERN) or external information (e.g., negative feedback, eliciting an FRN), depending on the extent to which these events are predictive of subsequent reward (or trial outcome). Several ERP studies (e.g., [13,21]) and neuroimaging studies [17] have yielded evidence consistent with this view.

As stated above, the reinforcement learning theory ("RL-ERN theory") predicts that an error-related negativity should be elicited by response errors and a feedback-related negativity by unexpected unfavorable outcomes such as negative performance feedback and stimuli indicating monetary losses. Importantly, one assumption of the RL-ERN theory holds that the ERN/FRN "... specifically indicates when the consequences of a response are worse than expected. This assumption is consistent with a fundamental principle of operant conditioning, which holds that learning should only occur when the reward or punishment is contingent on the animal's behavior." ([13] pp. 699). However, Yeung, Holroyd and Cohen [35] have recently demonstrated that the FRN can also be elicited by outcomes that are not contingent upon recent actions. This observation has been taken to suggest that the FRN reflects an evaluation of the motivational impact of outcomes and as such is associated with feedback signals in general instead of with feedback signals specifically related to recently executed actions. In the present study, we further tested this hypothesis by designing an experimental task, the "slot-machine task", that allowed us to study brain activity associated with both averted monetary gains as well as averted monetary losses in the complete absence of responding (cf. [1,2]).

In the slot-machine task, participants were asked to watch three digits presented successively on a computer screen. There were two experimental conditions. In the *gain condition*, participants gained a small amount of money if (and only if) the three digits were identical. Similarly, in the *loss condition*, participants lost a small amount of money if the three digits were identical. An important question was whether in this task unfavorable outcomes would elicit an FRN.

In addition to the slot-machine task, participants took part in two standard tasks for eliciting the ERN (a flanker task) and the FRN (a time estimation task). This enabled us to compare the ERN and the FRN to medial frontal negativities observed in the slot-machine task. Apart from analyzing the medial frontal negativities elicited in the slot-machine task, we also analyzed the stimulus-preceding negativity (SPN) and the P3. The SPN is a negative slow wave that could be observed preceding the presentation of the digits in the slot-machine task. Since the SPN is assumed to reflect anticipatory attention for an upcoming stimulus (for a review, see [30]), this analysis allowed us to verify whether participants attended to the presented stimuli and hence were really engaged in the task at hand. The P3 is a positive slow wave that is sensitive to the motivational significance and subjective probability of stimuli (e.g., [24]). We used the P3 as an index of subjects' expectations regarding the probability of the various stimulus sequences.

2. Materials and methods

2.1. Participants

Fourteen right-handed subjects, four men and ten women, between the ages of 18 and 23 (mean = 20 years) participated in the experiment. They were all healthy non-smokers and had normal or corrected-to-normal vision and hearing. Participants could earn course credits or money (5 €/h) or a combination of the two. In addition, all participants received a 10 € bonus at the end of one experimental task (see slot-machine task details below).

2.2. Experimental tasks and procedure

All participants took part in three experimental tasks: a slot-machine task [1], a time estimation task [20] and the arrow version of the flanker task [5]. Stimuli were presented at the center of a black monitor screen (14 in.) placed 1.25 m in front of the participant at eye level. The participants were seated in a comfortable chair in which response buttons – used in the flanker and time estimation task – were mounted into the armrest. The experiment was carried out in a dimly illuminated sound-attenuating and electrically shielded cabin.

In the slot-machine task, no responses were required, and the participants were asked to just watch three digits presented successively on the screen. The digits were colored white and ranged from 0 to 9. They had a maximum size of 1.5 cm by 1.2 cm and a maximum visual angle of 1.5°. Digits could appear in three possible orders, defining three trial types. First, all three digits could be identical (*xxx*; e.g., 1 1 1). Second, the last digit could be different from the first two (*xxy*; e.g., 5 5 8). And third, all digits could be different (*xyz*; e.g., 2 0 9). Overall, 25% of the trials were of the *xxx* type, 25% of the *xxy* type and 50% were of the *xyz* type. The three trial types were presented in pseudo-random order. On each trial, the three digits were chosen randomly within the constraints of the trial type for that trial. Thus, the probability that the second digit was identical to the first digit was 50%. Likewise, given that the first two digits were identical, the probability of receiving a third identical digit was also 50%. In this way, the participants were maximally uncertain as to whether the next digit in row would be the same or different. Stimuli were presented for 200 ms with an interstimulus interval (ISI) of 1 s. The mean intertrial interval (ITI) was randomized between 2100 and 4100 ms with a mean of 3100 ms.

The task was run under two conditions: a gain and a loss condition. In the *gain condition*, participants were told that they would gain 10 € cts every time three identical digits (*xxx*) were presented and that they would not gain anything whenever this was not the case (i.e., whenever the second (*xyz*) or third (*xxy*) digit was disconfirming a chain of identical digits). In the *loss condition*, participants were told that they would lose 10 € cts every time three identical digits (*xxx*) were presented to them and that they would not lose any money whenever this was not the case (i.e., *xyz* or *xxy*). At the start of the experiment, participants received a 10 € stake and were told they could keep the total amount of money that was left at the end of the experiment (which was always 10 €). Furthermore, the participants were told that the entire experiment (including time estimation task and flanker task) consisted of 12 blocks and that the computer would run a random number of blocks of the slot-machine task (gain as well as loss blocks), time estimation task and flanker task. In this way, participants were kept naive about which slot-machine task block would be their last, and so a prediction about their overall gain (or loss) at the beginning of the last slot-machine task block could not be made. Unknown to the participants, the experiment always started with four slot-machine task blocks, followed by two time estimation task blocks, followed by six flanker task blocks. The slot-machine task always consisted of two gain blocks and two loss blocks presented in one of four orders (ABBA, BAAB, AABB or BBAA). One block consisted of 100 trials. Before starting the experimental session, participants received a practice block of 100 trials with the gain condition.

Each trial of the time estimation task started with the presentation of a green square (1.2 cm × 1.2 cm) that was presented for 200 ms. Participants were asked to press a key when they thought a period of 1 s had elapsed following the onset of the square. Two seconds after stimulus presentation, participants received visual feedback about their 1-s estimate. An arrowhead pointing to the left indicated that their time estimation was too short, an arrowhead pointing to the right indicated that it was too long, and a combination of these arrowheads–pointing in opposite outer directions–indicated a correct estimation. The arrowheads had a vertical edge with a length of 1.5 cm and two tilted edges with a length of 2 cm.

The kind of feedback provided was a function of whether the duration of the participants' estimate fell within a time window. The window width was adjusted on the basis of the participants' performance on the preceding trial (+5 ms on both ends of the window when correct and −5 ms when incorrect). This procedure resulted in a global probability of correct and incorrect feedback of about 50% (see [20]). The initial window width was set at ±100 ms. Both blocks of the time estimation task consisted of 100 trials. The mean ITI was randomized between 2100 and 3100 ms with a mean of 2600 ms. Before starting the experimental session, participants received a practice block of 50 trials.

In the flanker task, participants were asked to produce a speeded response with either the left or the right index finger according to the direction of a central target arrowhead 'flanked' by two distractor arrowheads presented above and below the target. In congruent trials, two white arrowheads pointing in the same direction as the white target stimulus were presented above and below the target. In the incongruent condition, two arrowheads pointing in the direction opposite to the target stimulus direction were presented above and below the target. The arrowheads consisted of a vertical edge with a length of 1.5 cm and two tilted edges with a length of 2 cm. The edge-to-edge distance of flanker and target stimuli was 1° of visual angle.

Participants were instructed to focus on the central target and to ignore the flanker stimuli. They were asked to emphasize speed over accuracy of responding. Participants received six experimental blocks of 240 trials. Congruent (2/3 of the trials) and incongruent trials (1/3) were presented in a pseudo-random sequence. Half of the trials required a left-hand response and the other half of the trials required a right-hand response. The onset of the flanker stimuli preceded the onset of the target stimulus by 100 ms. The flanker stimuli remained on the screen for 200 ms, and the target stimulus was presented for 100 ms. All three stimuli were removed simultaneously. During the whole flanker task block, a central fixation dot stayed on screen. The central fixation dot merged into the central target when the central target was presented on the screen. The ITI was randomized between 800 and 2800 ms, and the mean ITI was 1800 ms. Two practice blocks of 100 trials preceded the experimental blocks.

2.3. Psychophysiological recordings

The electroencephalogram (EEG) was recorded from 50 BioSemi sintered Ag–AgCl electrodes (i.e., FPz, FP1, AF7, AF3, AFz, Fz, F1, F3, F7, FC5, FC1, FCz, Cz, C1, C3, C5, T7, TP7, CP3, CP1, Pz, P3, P5, P7, PO7, POz, O1, Oz, O2, PO8, P8, P6, P4, CP2, CP4, TP8, T8, C6, C4, C2, FC2, FC6, F8, F4, F2, AF4, AF8, FP2, M1, M2). The electrodes were mounted into a head-cap and affixed to the scalp with Parker Signa-Gel according to an extended 10–20 system montage. The BioSemi system replaces the reference electrode(s) used in more conventional systems with a common mode sense (CMS) active electrode and a driven right leg (DRL) passive electrode. In this way, any electrode or combination of electrodes can be the "reference," and the choice is made during offline analysis. The electrooculogram (EOG) was recorded from six sintered Ag–AgCl electrodes. One pair of electrodes was placed in a straight line at the outer canthi of the left and right eye to monitor horizontal eye movements. The other two pairs were placed in a straight line above and below each eye to monitor blinks and vertical eye movements. The data from all channels were amplified with the ActiveTwo AD-box and were digitized with a 24-bit resolution at a rate of 256 Hz.

2.4. Data analyses

The EEG signals of all tasks were referred algebraically to linked mastoids. With respect to the slot-machine task, we were interested in medial frontal negativities as well as in slow waves like the stimulus-preceding negativity (SPN) and in the P3. For these purposes, the data were bandpass filtered using different parameters. In the first series of analyses, the data were filtered using a 2–12 Hz bandpass filter, which removes low-frequency waves from the EEG. In the second series of analyses, we used a wide band 0.01–25 Hz Butterworth zero-phase filter to investigate the low-frequency SPN and the P3. In both series of analyses, segments of 3200 ms of data (200 ms baseline) were extracted separately for the *xxx*, *xxy* and *xyz* trial types from the continuous data file. This was done for the gain as well as for the loss condition. All segments were synchronized to the onset of the first slot-machine task stimulus. They were then corrected for EOG artifacts using the procedure described by Gratton, Coles and Donchin [10]. Subsequently, they were checked for other artifacts using an automatic rejection procedure: segments were excluded from further analyses when the minimum and maximum amplitude in the segment differed more than 200 μV[2]. In the slot-machine task, the medial frontal negativity was scored separately for each individual subject and defined as the most negative peak in the interval between 150 and 400 ms after presentation of the third stimulus relative to the immediately preceding positivity. The stimulus-preceding negativity was scored as the average value in the interval between 1150 and 1250 ms after presentation of the second stimulus relative to a baseline of 200 ms after presentation of the second stimulus. Finally, the P3 was scored as the most positive peak in the interval between 200 and 600 ms after presentation of the third stimulus. Statistical analysis was done with repeated measures multivariate analysis of variance (MANOVA) in order to cope with the different correlations between electrode sites [32]. Analyses of the mediofrontal negativity were restricted to electrodes F3, Fz, F4, C3, Cz and C4. Within-subjects factors were Condition (Loss versus Gain), Trial type (*xxx*, *xxy*, *xyz*), Location (Frontal, Central) and Laterality (Left, Middle, Right). The analyses of the SPN and the P3 were focused on electrodes F3, Fz, F4, C3, Cz, C4, P3, Pz and P4. Within-subjects factors were Condition (Loss versus Gain), Trial type (*xxx*, *xxy*, *xyz*), Location (Frontal, Central, Parietal) and Laterality (Left, Middle, Right).

The EEG signals of the time estimation task were digitally filtered using a 2–12 Hz bandpass filter. A segment of 2700 ms of data was extracted (200 ms baseline) separately for correct and incorrect feedback stimuli. The segments were synchronized to the onset of the feedback stimulus and corrected for EOG artifacts as described above. They were then checked for other artifacts by using an automatic rejection procedure in which segments were excluded from further analyses when the minimum and maximum amplitude in the segment differed more than 100 μV. The FRN in the time estimation task was scored separately for each individual subject and defined as the most negative peak in the interval between 150 and 400 ms after feedback presentation relative to the immediately preceding positivity. Statistical analysis was done with repeated measures multivariate analysis of variance (MANOVA). Analyses were done on electrodes Fz, Fcz and Cz. Within-subjects factors were Feedback (Correct versus Incorrect) and Location (Frontal, Frontocentral, Central).

The EEG signals of the flanker task were also digitally filtered using a 2–12 Hz bandpass filter. A segment of 1250 ms of data (750 ms before the response and 500 ms thereafter) was extracted separately for correct and incorrect reactions from the continuous data file (baseline −500 to −400 before response[3]). The segments were synchronized with respect to the response and corrected for EOG and other artifacts as described above. For each subject, the ERN was scored as the most negative peak in the interval between 25 and 125 ms after response onset registration relative to the immediately preceding positivity. Statistical analysis was done with repeated measures multivariate analysis of variance (MANOVA). The analyses were done on channels F3, Fz, F4, C3, Cz and C4. Within-subjects factors were Accuracy (Correct reaction versus Incorrect reaction), Location (Frontal, Central) and Laterality (Left, Middle, Right).

[2] The rejection criteria were set to this value for the analyses of the P3 and SPN in the slot-machine task, for which wide bandpass filter settings (0.01–25 Hz) were used. These settings allow more drifting of the EEG signal. Hence, if the standard value of 100 μV was used, too many trials were (erroneously) rejected.

[3] We chose this early time window to ensure that the baseline was not confounded by differences in the amplitude of the P3 or other components.

3. Results

3.1. Slot-machine task

The ERPs (bandpass-filtered between 2 and 12 Hz) for the three different trial types (*xxx*, *xxy*, *xyz*) in the slot-machine task are depicted in Fig. 1. A first thing to note is that the pattern of results for the loss condition (left panel) and for the gain condition (right panel) is very similar. Statistical analysis of the ERPs elicited by the second and third stimulus revealed that there was neither a significant main effect of Condition (loss/gain), $F\text{s}(2,12) < 1$, nor any significant interaction effect including this factor. Furthermore, at about 250 ms after presentation of the second, $F(2,12) = 7.96$, $P = 0.006$, as well as the third stimulus, $F(2,12) = 8.48$, $P = 0.005$, highly significant differences between the three different trial types were observed. The negativity elicited when the second stimulus differed from the first (i.e., *xyz* trials) was significantly larger than that observed for *xxy* trials, $F(1,13) = 13.65$, $P = 0.003$, and *xxx* trials, $F(1,13) = 17.24$, $P < 0.001$. The scalp distribution of the observed negativity had a midline maximum, $F(1,13) = 6.90$, $P < 0.01$, and there was no reliable difference between the frontal and central electrode positions, $F(1,13) = 4.06$, $P > 0.05$. The negative deflection elicited by the third stimulus was larger on *xxy* trials than on *xyz* trials, $F(1,13) = 6.97$, $P < 0.02$, and on *xxx* trials, $F(1,13) = 17.90$, $P < 0.001$. In addition, the negativity for *xyz* trials was greater

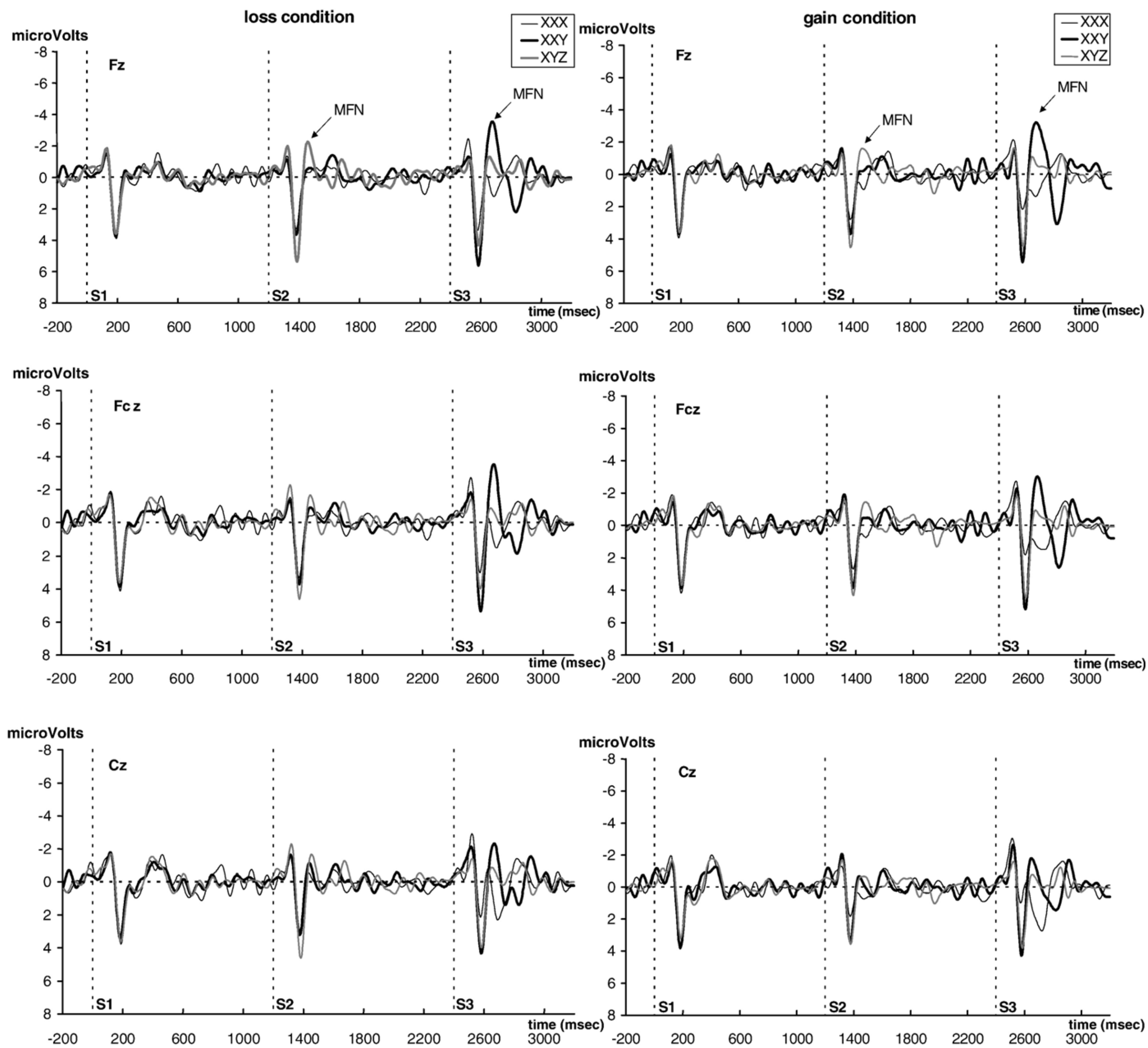

Fig. 1. Stimulus-locked grand average waveforms (filtered 2–12 Hz) from electrodes Fz, Fcz and Cz evoked by *xxx*, *xxy* and *xyz* trials in the slot-machine task. Left panel: loss condition, right panel: gain condition.

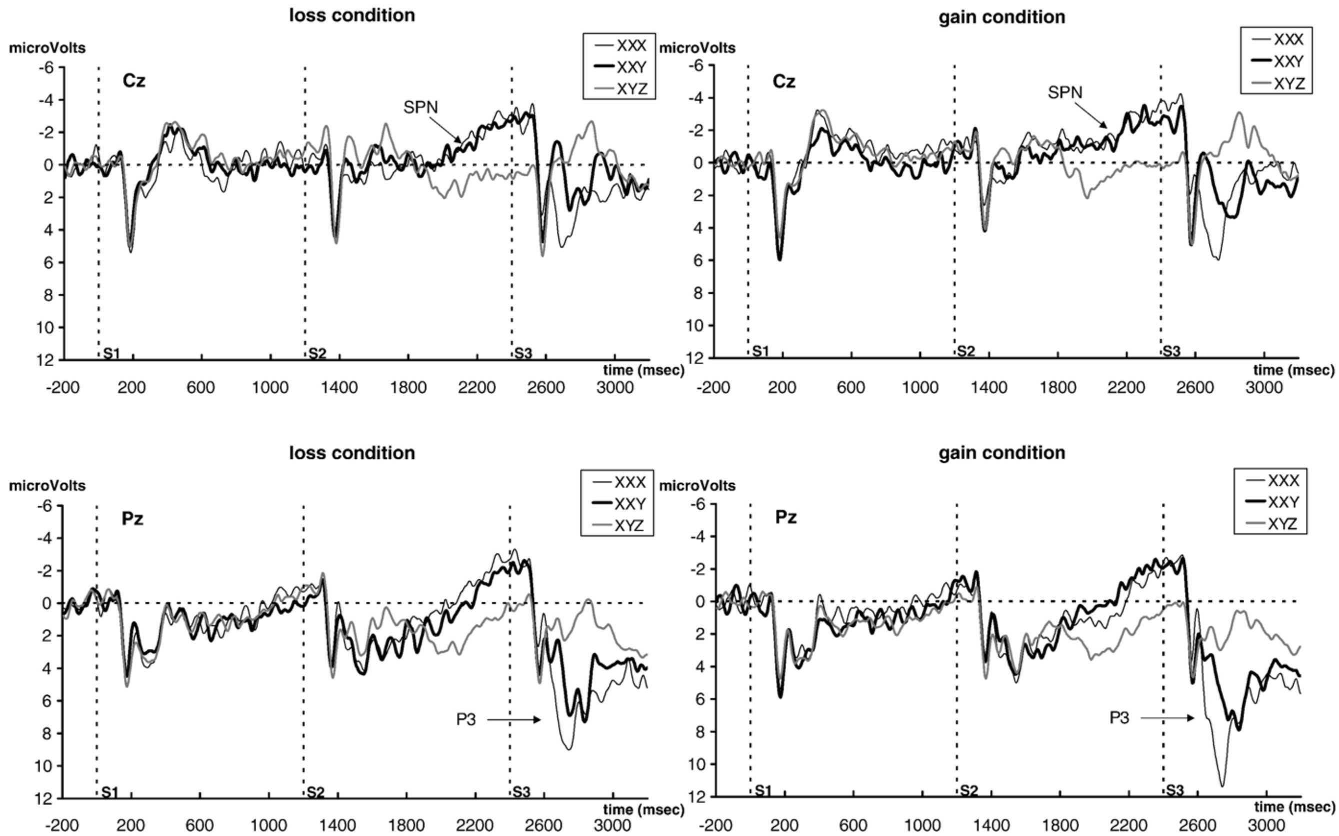

Fig. 2. Stimulus-locked grand average waveforms (filtered 0.01–25 Hz) from electrodes Cz and Pz evoked by *xxx*, *xxy* and *xyz* trials in the slot-machine task. Left panel: loss condition, right panel: gain condition.

than that for *xxx* trials, $F(1,13) = 9.31$, $P < 0.01$. The negativity after the third stimulus on *xxy* trials had a midline maximum, $F(2,12) = 14.85$, $P < 0.001$, and was greater at frontal than at central electrodes, $F(1,13) = 17.35$, $P < 0.005$. Further statistical comparisons [2 (condition) $\times$ 3 (trial type) $\times$ 2 (electrode position)] revealed that, although the observed negativity was numerically larger at Fz than at FCz, this difference did not reach significance, $F(1,13) < 1$. In summary, the results show that in the slot-machine task a mediofrontal negativity was observed whenever a stimulus was different from the preceding one, irrespective of whether that stimulus averted a loss or a gain. In addition, the mediofrontal negativity was specifically pronounced if the third stimulus deviated from the preceding two stimuli[4].

Although no behavioral measures were available to ascertain that participants were engaged in the slot-machine task, the ERP differences between the three trial types suggest that participants did attend to the stimuli, even though the task did not require any response. To further verify this notion, we analyzed the SPN preceding the presentation of the third stimulus. As can be seen in Fig. 2, the SPN was larger if the third stimulus could still result in a loss (left panel) or gain (right panel) (i.e., in the *xxy* and *xxx* conditions), as compared to when the second stimulus had already averted a loss or gain (in the *xyz* condition), $F(2,12) = 20.17$, $P < 0.002$. The interaction between Trial type and Condition was not significant, $F(1,13) = 0.62$, $P = 0.49$. Furthermore, the SPN was largest at central electrode locations, $F(2,12) = 9.19$, $P < 0.003$, and tended to have a right hemisphere preponderance, $F(2,12) = 4.01$, $P = 0.052$.

We also analyzed the P3 to determine whether the amplitudes of the mediofrontal negativity and the P3 showed a similar sensitivity to the various trial types. As expected, the P3 had a midline maximum, $F(2,12) = 19.36$, $P < 0.0001$, and was largest at the parietal electrodes, $F(2,12) = 11.63$, $P = 0.002$. Furthermore, in clear contrast to the mediofrontal negativity, which was largest on *xxy* trials, the largest P3 amplitudes were observed for the *xxx* trial type (see Fig. 2). This was expressed in a significant main effect of Trial type, $F(2,12) = 13.95$, $P = 0.002$. Follow-up pair-wise comparisons indicated that the P3 associated with *xxx* trials was larger than the P3s associated with *xxy* trials, $F(1,13) = 8.30$, $P < 0.013$, and *xyz* trials, $F(1,11) = 10.36$, $P < 0.007$. Finally, although the P3 amplitude for the *xxx*

[4] In an additional analysis, we averaged only the last gain and loss blocks for each participant (e.g., AABB). These averages showed essentially no differences to the averages of the overall data set. This excludes the possibility that the overall results were substantially influenced by discrepancies between the subjectively expected and actual probability structure of the task. For example, given the large set of digits used (0–9), it is possible that participants were initially surprised about the high number of *xxx* trials (i.e., 25%).

trial type was slightly larger in the gain condition than in the loss condition, it did not reliably differ between the gain and loss conditions, $F(1,13) = 4.06$, $P = 0.065$.

3.2. Time estimation task

The average window width on the basis of which correct or incorrect feedback was given ranged from 905 ms to 1095 ms (i.e., ±95 ms) across participants. As expected, the tracking algorithm yielded an equal percentage of correct (50.7%) and incorrect feedback.

Fig. 3 presents the feedback-locked ERP waveforms for correct and incorrect feedback trials in the time estimation task. The FRN that can be observed at about 250 ms after feedback presentation reached a significantly higher amplitude on incorrect feedback trials than on correct feedback trials, $F(1,13) = 6.36$, $P = 0.026$, at the midline electrode channels (Fz, Fcz and Cz). Furthermore, the FRN was larger at Fz [$F(2,12) = 26.39$, $P < 0.001$] and FCz [$F(2,12) = 49.78$, $P < 0.001$] than at Cz. A direct comparison between electrodes Fz and Fcz showed that, although the FRN was numerically larger at electrode Fcz, this difference did not reach significance $F(1,13) = 0.90$, $P = 0.36$.

3.3. Flanker task

The behavioral results for the flanker task were similar to results previously reported for this task (e.g., [19]). Table 1 lists the mean RTs and trial proportions in the flanker task as a function of flanker congruency and accuracy. Participants responded faster on congruent than on incongruent trials, $F(1, 13) = 104.10$, $P < 0.0001$, and faster on incorrect trials than on correct trials, $F(1, 13) = 131.62$, $P < 0.0001$. Furthermore, a significant interaction between flanker congruency and accuracy was observed, $F(1, 13) = 543.93$, $P < 0.0001$. Simple effect analyses showed that on congruent trials there was no reliable difference between correct and incorrect RTs, $F(1, 13) = 0.07$, $P = 0.80$, whereas, on incongruent trials, participants responded faster on error trials than on correct trials, $F(1, 13) = 418.01$, $P < 0.0001$. In addition, participants produced more errors on incongruent trials than on congruent trials, $F(1, 13) = 24.59$, $P = 0.0003$.

Table 1
Mean reaction times and trial proportions ($N = 14$) in the flanker task as a function of flanker congruency and accuracy

Trial type	Correct reactions		Incorrect reactions	
	RT	Probability	RT	Probability
Congruent	459	0.88	458	0.12
Incongruent	546	0.70	448	0.30

Fig. 4 presents the response-locked ERP waveforms for the correct and incorrect trials, averaged across congruent and incongruent trials. The ERN, peaking at about 70 ms after the response, reached a significantly higher amplitude on incorrect than on correct trials, $F(1,13) = 34.78$, $P < 0.001$. The ERN had a midline maximum, $F(2,12) = 4.94$, $P = 0.027$, and was greater at frontal than at central electrodes, $F(1,13) = 9.16$, $P < 0.01$. An additional analysis indicated that the ERN was larger at electrode FCz than at electrode Fz, $F(1,13) = 4.90$, $P = 0.045$.

3.4. Correlations

Table 2 presents product–moment correlations between the peak amplitudes (Fcz) associated with averted gains and losses in the slot-machine task, incorrect feedback in the time estimation task and incorrect reactions in the flanker task. As can be seen, the amplitudes of the mediofrontal negativities recorded in the slot-machine task and the FRN recorded in the time estimation task showed high inter-correlations. The amplitude of the ERN recorded in the flanker task did not correlate with the amplitude of the other components.

3.5. Current source densities

Fig. 5 presents current source density (CSD) maps (see, [25,26]) associated with the peak latency (at FCz) of the mediofrontal negativity, FRN and ERN in the three tasks.

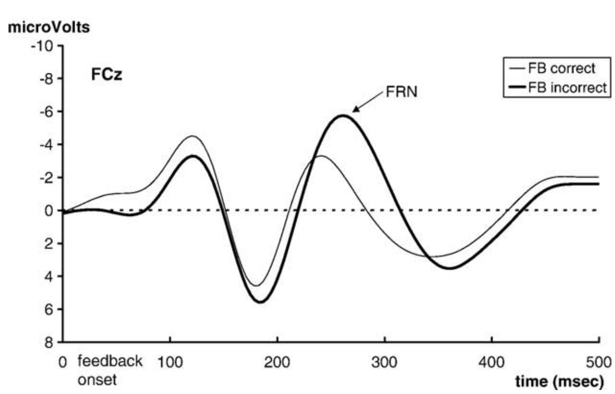

Fig. 3. Stimulus-locked grand average waveforms (filtered 2–12 Hz) from electrode Fcz evoked by correct and incorrect feedback in the time estimation task.

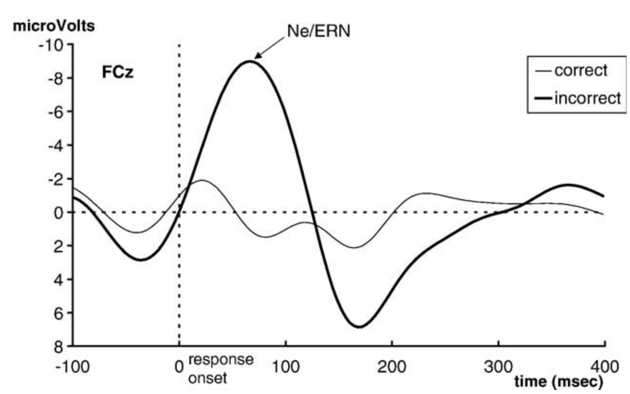

Fig. 4. Response-locked grand average waveforms (filtered 2–12 Hz) from electrode Fcz evoked by correct and incorrect reactions in the flanker task.

Table 2
Between-subjects Pearson product–moment correlations (*df* = 13) between mediofrontal negativity, FRN and ERN peak amplitudes recorded at electrode Fcz in the three tasks

Task	Slot-machine		Time estimation	Flanker
	Averted loss	Averted gain		
Averted loss Slot-machine	1.00	0.69*	0.70*	0.21
Averted gain		1.00	0.71*	0.34
Time estimation			1.00	0.52
Flanker				1.00

* Significant at the 0.01 level (2-tailed).

The left panel of Fig. 5 depicts the CSD maps for respectively an averted loss or an averted gain in the slot-machine task, incorrect feedback in the time estimation task and incorrect reactions in the flanker task. The right panel of Fig. 5 shows CSD maps based on difference waves in these tasks. As can be seen, the CSD maps for the ERN in the flanker task and FRN in the time estimation task show a highly similar mediofrontal scalp distribution. In contrast, the CSD maps for the mediofrontal negativities in the slot-machine task show a more diffuse, frontal and right-lateralized scalp distribution.

4. Discussion

Yeung et al. [35] have recently shown that the feedback-related negativity (FRN), an ERP component associated with the processing of unfavorable outcomes, can be elicited by outcomes that are not contingent upon recent actions. This observation has been taken to suggest that the FRN reflects an evaluation of the motivational impact of outcomes and as such is associated with feedback signals in general instead of with feedback signals specifically related to recently executed actions (cf. [13]). We attempted to replicate and extend the findings of Yeung et al. [35] by designing a slot-machine task in which brain activity associated with monetary gains and losses could be studied in the complete absence of responding. In addition, we compared the ERP results from the slot-machine task with the ERPs recorded in two standard tasks known to elicit the error-related negativity (ERN) and the FRN. In line with the RL-theory, we predicted that any FRN-like potential observed in the slot-machine task would be larger following losses in the loss condition and averted gains in the gain condition than following gains in the gain condition and averted losses in the loss condition.

The results we obtained may be summarized as follows. First, we found an FRN-like mediofrontal negativity associated with outcomes in the slot-machine task, although these outcomes were not preceded by any choice or action of the participant. A second and rather unanticipated result was that the conditions under which this negative component was elicited were different than would be expected of the FRN on the basis of the RL-theory: It was elicited whenever a stimulus was *different* from the preceding stimulus, irrespective of whether that stimulus averted a loss or a gain. Furthermore, the mediofrontal negativity was specifically pronounced if the third stimulus deviated from the preceding two stimuli (i.e., *xxy* trials). To attest whether participants attended to the presented stimuli and hence were really engaged in the slot-machine task, we recorded the SPN. The SPN results showed that the participants did attend to the stimuli, event though the task did not require a response. The SPN amplitudes proved to be especially large when the third stimulus could still result in a gain or loss (i.e., the *xxy* and *xxx* conditions). In the remainder of the Discussion, we will discuss the relationship between the mediofrontal negativity observed in the slot-machine task, the ERN, FRN and other medial frontal negativities, and we will evaluate the possible implications of our results for theories of performance monitoring.

In order to verify to what extent the mediofrontal negativity in the slot-machine task resembled the FRN in the time estimation task and/or the ERN in the flanker task, we compared the three components with respect to morphology, latency, amplitude and scalp distribution. The morphology of the three components was similar. Furthermore, the mediofrontal negativity and FRN had comparable peak latencies (~250 ms). Perhaps most remarkably, the amplitudes of the mediofrontal negativities associated with averted gains and averted losses were highly correlated not only with each other but also with the amplitude of the FRN. In contrast, no significant correlation was found between the amplitudes of the mediofrontal negativity and ERN. These findings seem to suggest that a similar process–which seems to be evaluative in nature–gives rise to the FRN and the mediofrontal negativity observed in the slot-machine task.

In apparent contrast with this possibility, the mediofrontal negativity observed in the slot-machine task had a more right-lateralized and anterior scalp distribution than the FRN, whose scalp distribution was nearly identical to that of the ERN. Yet, although this result might be taken as evidence against the possibility that the mediofrontal negativity and FRN reflect a similar neural process, an alternative interpretation is that the mediofrontal negativity reflects the summed activity of two neural generators: one that gives rise to the frontocentral scalp distribution that is usually found for the FRN and an additional neural generator that is specific to the slot-machine task used here. Together, they lead to the right-lateralized mediofrontal scalp distribution of the slot-machine negativity. Other gambling studies have reported a similar right lateralization and have also considered the possibility that more than one neural generator is active in situations in which feedback about monetary gains and losses is delivered to participants (see, e.g., [8,23]).

In summary, although overall the evidence regarding the similarity between the three ERP components is incon-

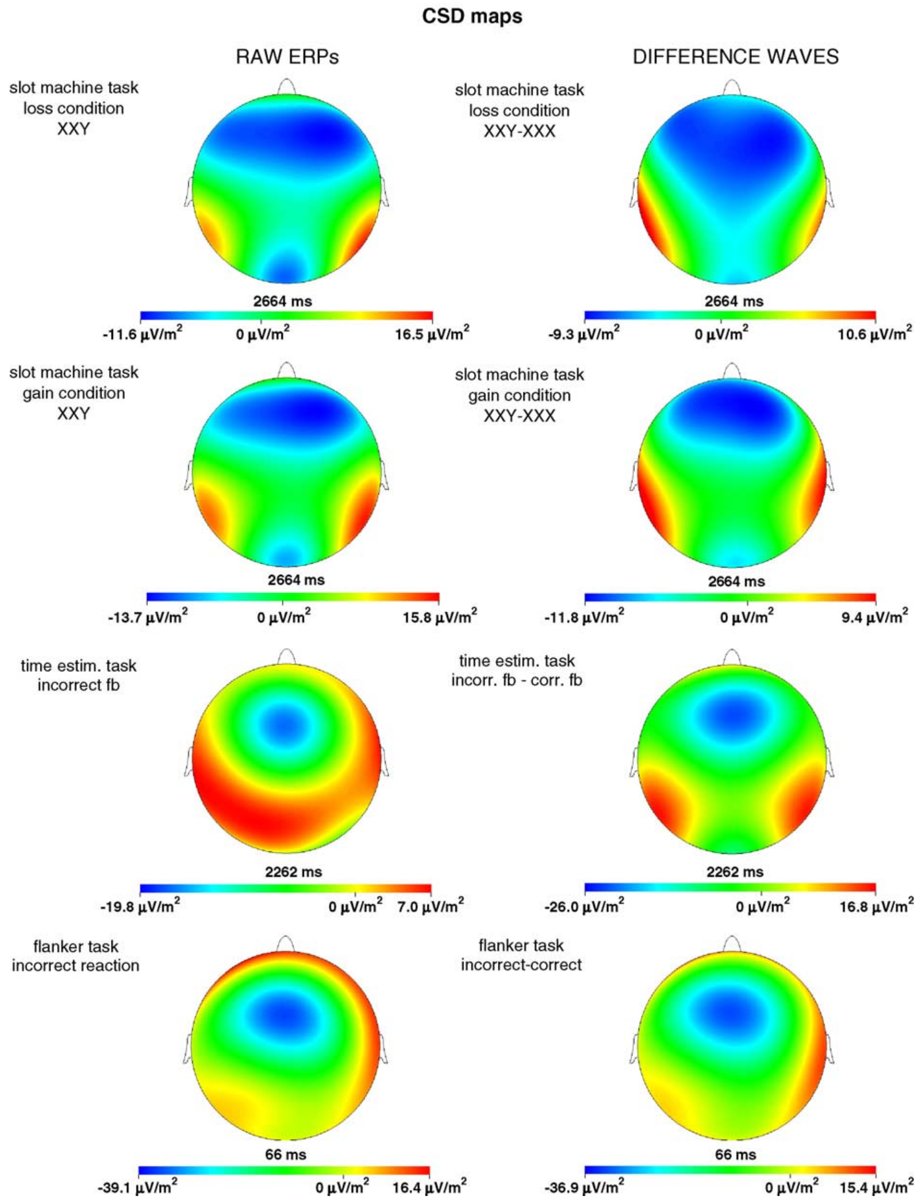

Fig. 5. Current source density (CSD) maps at the time of the component peaks associated with averted gains and averted losses in the slot-machine task, incorrect feedback in the time estimation task and incorrect reactions in the flanker task. CSDs in left panel are based on raw ERPs, CSDs in right panel are based on difference waves.

clusive, the results illustrate that there are close resemblances concerning the morphology, latency, amplitude and, albeit to a lesser extent, scalp topography of the mediofrontal negativity observed in the slot-machine task and, in particular, the FRN observed in the time estimation task.

If the mediofrontal negativity and FRN are manifestations of the same underlying process, this would have implications for the RL-theory of Holroyd and Coles [13]. One of the original assumptions of the RL-theory stated that an FRN should only be observed when negative outcomes are experienced in relation to executed actions. We did however observe an FRN-like potential after an averted gain in a task in which responses were entirely absent. If we assume that the observed mediofrontal negativity is actually an FRN, then our findings contribute to the earlier statement of Yeung et al. [35] that the RL-theory might need to be extended to include learning that is not specifically related to recently executed actions. Apart from a mediofrontal negativity following averted gains, we also observed a negativity following averted losses. This finding was unexpected and is difficult to reconcile with the predictions of the RL-theory regarding the FRN. Similar arguments apply to theories claiming that the FRN reflects the binary classification of outcomes as good or bad [33,11].

Therefore, the question arises whether we might be able to link the mediofrontal negativity observed in the slot-machine task to alternative ERP components in the psychophysiological literature. In this respect, a possible candidate would be the N2, a frequency-sensitive negative component typically elicited by attended deviant stimuli or stimulus categories, irrespective of whether these require a response (see [27], for a review). There are various similarities between the mediofrontal negativities observed in the slot-machine task and the N2. First, the components have a similar timing and morphology (see also [12]). Second, the N2 is often elicited by stimuli that deviate from the prevailing stimulus context. This is also the case for the negativities in the slot-machine task, which were elicited when a digit was different from the preceding digits and hence averted a gain or a loss. And, third, the N2 has a medial, central or frontocentral scalp distribution, similar to that of the mediofrontal negativity. Given the several properties that the mediofrontal negativity and N2 have in common, the question is justified whether the mediofrontal negativity might be an N2 instead of an FRN.

However, there is also a compelling argument against the notion that the N2 and mediofrontal negativity reflects the same cognitive process. The N2 is typically followed by the P3, and both components (often referred to as the "N2/P3 complex") show a similar sensitivity to various experimental factors. For example, both the N2 and P3 are specifically pronounced for subjectively unexpected stimuli. According to Squires, Wickens, Squires and Donchin [29], the N2/P3 complex is dependent on decaying memory for stimuli within the prior stimulus sequence, the specific structure of the stimulus sequence and the global probability of event occurrence. Although the slot-machine task was designed such that the probability of a digit being identical to the previous sequence was always 50%, a *y* stimulus following two *x*s might have appeared as a subjectively unexpected event. Note that, if this were the case, then the amplitude of the P3 should have been largest on *xxy* trials. However, in contrast to this prediction, the P3 was largest in amplitude on *xxx* trials. It is not evident why, in the present experiment, disconfirming stimuli would elicit a pronounced N2 but fail to elicit a large P3. Although the mediofrontal negativity observed on *xxy* trials shares common properties with the N2, the pattern of P3 results casts doubt on the conclusion that the mediofrontal negativity observed in the present study and the N2 are the same component. Moreover, this hypothesis does not address the high correlation between the amplitudes of the mediofrontal negativity and the FRN. In summary, we do not believe that our results could be explained by assuming that the observed mediofrontal negativity is simply an N2.

Another possibility is that the mediofrontal negativity observed after averted gains and losses reflects contributions of both the FRN and the N2. The design of the present study makes it difficult to determine to what extent the stimulus probability effects of the N2 influenced the observed mediofrontal negativity, but they do not contradict such an interpretation. In a follow-up study [4], we tested this hypothesis more directly. Previous research found the FRN to be sensitive to valence of outcome as well as to stimulus probability [15], while the N2 is sensitive to stimulus probability only. In the follow-up study, two gain/loss probability conditions were added, and difference waves between averted gains and losses were computed for each probability condition. This procedure controlled for the effect of stimulus probability and thus essentially removed the contribution of the N2 from the ERP. The resulting FRN difference waves increased in a linear fashion with the unexpectedness of *xxy* trials, consistent with the predictions of the RL-theory. These findings lend support to the hypothesis that the mediofrontal negativity observed in the present study reflects contributions of both the FRN and the N2.

The current study provides a demonstration of the difficulties that researchers face in explaining the various medial frontal negativities observed in ERP studies (cf. [8,23]). The question to what extent these ERP components are manifestations of the same underlying process is of key importance for the development of theories of performance monitoring. Although currently none of the existing theories is able to account for all of the medial frontal negativities, vital attempts have been made to provide unifying accounts of the ERN and FRN [13], ERN and N2 [31,34] and FRN and N2 [12]. The results of the present study provide another challenge for these theories by demonstrating an ERP component that correlates with and bears close resemblance to the FRN that–like the N2–is elicited by stimuli that deviate from the preceding stimulus sequence and that occurs even in the absence of responding.

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