Electrophysiological correlates of error correction

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Abstract

Evidence in the literature for the proposed relationship between the error-related negativity (ERN) and error correction is rather limited and inconsistent. We investigated corrective behavior and the ERN in two groups of participants who performed a flanker task. The correction-instructed group was asked to immediately correct all encountered errors. The noninstructed group was unaware that corrective responses were recorded. We found a negative deflection following corrected errors that peaked at 200–240 ms after the error. We refer to this negativity in the ERP waveform as correction-related negativity (CoRN). We assume that the correction-related negativity reflects evaluative functions of the motor system necessary for error corrections. ERN latency and amplitude were modulated by the occurrence and temporal characteristics of immediate corrections. These results are discussed within the framework of current models of performance monitoring.

Descriptors: Error correction, Error detection, Error-related negativity (ERN), Correction-related negativity (CoRN)

Whereas over the last decade research has mostly focused on error detection, the consequences of error detection—remedial actions—are less investigated and require further attention. The present study provides a first attempt to close this research gap by investigating the event-related potential (ERP) correlates of error correction. It builds on previous behavioral and ERP findings concerned with performance monitoring and extends these to the domain of error correction behavior.

ERP studies revealed a negative voltage component associated with errors, the error negativity (Ne; Falkenstein, Hohnsbein, Hoormann, & Blanke, 1990) or error-related negativity (ERN; Gehring, Goss, Coles, Meyer, & Donchin, 1993). It starts at the onset of the electromyographic (EMG) activity preceding the overt error response and peaks about 50 to 100 ms thereafter (Gehring et al., 1993; Kopp Rist, & Mattler, 1996). The ERN is fronto-centrally distributed over the scalp and presumably generated in the anterior cingulate cortex (ACC; Carter et al., 1998; Dehaene, Posner, & Tucker, 1994; Ullsperger & von Cramon, 2001, 2004), specifically in the human homolog of the monkey rostral cingulate motor area (rCMA), called the rostral cingulate zone (RCZ; cf. Picard & Strick, 1996).

It has been shown that the ERN is typically present when executed errors are easy to detect by the individual (action slip). An ERN-like wave is also elicited by external error feedback in reinforcement learning tasks (the feedback ERN; Badgaiyan & Posner, 1998; Holroyd & Coles, 2002; Miltner, Braun, & Coles, 1997), indicating at least the partial independence of error processing from the motor system. Furthermore, the ERN is unaffected by perceptual properties of the stimuli (Bernstein, Scheffers, & Coles, 1995), stimulus modality (Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991), and response modality (Falkenstein, Hoormann, Christ, & Hohnsbein, 2000; Gehring & Fencsik, 2001; Holroyd, Dien, & Coles, 1998; Miltner et al., 1997; Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001); however, the ERN appears to be modulated by individual error salience (Bernstein et al., 1995; Gehring, Himle, & Nisenson, 2000; Luu, Collins, & Tucker, 2000; Pailing, Segalowitz, Dywan, & Davies, 2002; Ullsperger & Szymanowski, 2004).

A second ERP component has been described to be associated with errors, the error positivity (Pe; Falkenstein et al., 1990, 2000). It is a parietally distributed positivity occurring about 300–500 ms after the response, the functional significance of which is still rather unclear. As Falkenstein (2004) pointed out, three hypotheses for the Pe have been proposed. First, the Pe could reflect conscious error recognition (Falkenstein et al., 2000; Leuthold & Sommer, 1999; Nieuwenhuis et al., 2001); second, it could be an adaptation of response strategy (Leuthold & Sommer, 1999; Nieuwenhuis et al., 2001; but see Ullsperger & Szymanowski, 2004, for conflicting findings), or third, it could be subjective/emotional error processing (van Veen & Carter, 2002).

Error Correction

There is empirical evidence that errors result in adjustments to reach the intended goal and/or to prepare efficient behavior in similar subsequent situations. For example, participants slow down their responses following the occurrence of an error, the socalled post-error slowing effect (Rabbitt, 1966b). In addition, they mostly show overt corrective responses following errors. Behavioral studies reported that participants tended to correct their responses immediately after they had committed an error

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without being given an external signal that an error had occurred (Cooke & Diggles, 1984; Rabbitt, 1966a, 1966b). These errorcorrecting responses were significantly faster than correct responses. A behavioral study by Rabbitt (2002) investigated error correction and error signaling in a serial-choice reaction-time task. In line with previous findings, participants quickly and accurately corrected most of their errors. Rabbitt (2002) argued that these very fast error corrections are "delayed correct responses," initiated almost in parallel with the erroneous response and following briefly after them. Latest findings demonstrated that if participants are not instructed to correct errors, they allowed the majority of errors to remain uncorrected. In contrast, if they have been instructed to correct their errors, the percentage of error corrections can be raised up to nearly 100% (Fiehler, Ullsperger, & von Cramon, 2004). This gain in correction rate can be attributed to an intentional process and depends on the instructional context. Whether this intentional gain in error correction requires error detection remains an open question.

Few psychophysiological studies have systematically investigated the relationship between ERP components and error correction. These studies revealed inconsistent findings about whether ERN amplitude and latency vary as a function of whether errors are corrected or not. Concerning ERN amplitude, Gehring et al. (1993) observed a modulation of the ERN by error correction. The authors demonstrated that the larger the ERN, the greater the probability that the error would be corrected. Consistent with this result, Falkenstein, Hohnsbein, and Hoormann (1994) showed a larger ERN amplitude for corrected compared to uncorrected errors; however, this effect was only found after auditory and not after visual stimuli. In contrast, a later study of the same group reported an enhanced ERN amplitude for corrected than uncorrected errors after both auditory and visual stimuli (Falkenstein, Hohnsbein, & Hoormann, 1996). This finding was strengthened by recently published data showing a larger ERN for corrected than uncorrected errors (Rodriguez-Fornells, Kurzbuch, & Münte, 2002). Furthermore, this study revealed an increased ERN amplitude for fast compared to slow error corrections.

Inconsistent findings have also been reported with regard to ERN latency. Falkenstein et al. (1994) observed no latency differences of the ERN between corrected and uncorrected errors after either auditory or visual stimuli. In a later experiment of the same group, a modulation of ERN latency between corrected and uncorrected errors was exhibited revealing a later peak for uncorrected compared to corrected errors after both auditory and visual stimuli (Falkenstein et al., 1996). In contrast, a study by Rodriguez-Fornells et al. (2002) did not find latency differences of the ERN between corrected and uncorrected errors, nor between slow and fast error corrections.

Aims of the Study

Given the inconsistent picture of the relationship between the ERN and error correction provided by the literature, we investigated the time course of immediate error correction by means of behavioral data and ERPs. Furthermore, we studied whether correction speed modulates error-related ERP components.

To investigate corrective behavior, participants were randomly divided into two groups. One group was instructed to immediately correct all encountered errors (correction-instructed group), and a second group was unaware that corrective responses were recorded (noninstructed group). A similar design was used in the study by Rodriguez-Fornells et al. (2002) with an important difference. Whereas in their study error correction was *forbidden* in one condition, we merely did not instruct immediate corrective behavior. Our design offers two noteworthy advantages: First, we can rule out additional processes of control or inhibition due to the prohibition of error correction, and second, we can conduct a supplementary comparison between incidental and intentional error correction to get a more detailed view of the error correction process.

Taking previous findings into account, the following predictions can be made. Both the correction-instructed group and the noninstructed group should show error correcting responses (e.g., Rabbitt, 1966a, 1966b); however, the correction-instructed group should commit significantly higher correction rates than the noninstructed group (e.g., Fiehler et al., 2004). Based on the majority of previous ERP studies one should expect a larger ERN amplitude for corrected than uncorrected errors (Falkenstein et al., 1996; Gehring et al., 1993; Rodriguez-Fornells et al., 2002; but see Falkenstein et al., 1994) and a similar ERN time course of these two conditions (Falkenstein et al., 1994; Gehring et al., 1993; Rodriguez-Fornells et al., 2002; but see Falkenstein et al., 1996). Moreover, ERN amplitude should be modulated by correction speed exhibiting a larger ERN for quickly compared to slowly corrected errors (Rodriguez-Fornells et al., 2002).

Methods

Participants

Forty-four individuals participated in the experiment. They were randomly divided into two groups: In one group, participants were instructed to correct their errors immediately by pressing the correct button after an erroneous response (correction-instructed group) and in the second group, the possibility to correct errors was not mentioned in the instruction (noninstructed group). It is important to note that all participants were naive to the experiment and did not participate in any previous experiment involving immediate error correction. Data from 4 participants were excluded from analyses, 2 participants for an error rate below 10% resulting in an insufficient number of error trials to form meaningful ERPs and 2 participants for disregarding the experimental instruction. The sample of 40 participants (21 female) was right-handed and had normal or corrected-to-normal vision. They ranged in age from 20 to 31 years (M = 24, SEM = 0.4). Written informed consent according to the Declaration of Helsinki was obtained from each participant and the rights of the participants were protected. They were paid for participation.

Procedure

A speeded modified flankers task known to elicit the ERN was used in the study (Ullsperger & von Cramon, 2001). The experiment comprised five experimental blocks of 10 min. After each block, participants had the possibility to relax for a short time before the next block started. In the task, participants were presented with a fixation mark for about 500 ms at the center of a screen, after which four flanker arrows occurred for 110 ms. The arrows were 0.46° tall and 1.08° wide, and appeared 0.52° and 1.04° above and below the screen center. The target arrow was presented for 30 ms in the center of the flanker arrows; its onset was delayed by 80 ms from the flanker's onset. In 45% of trials (540 trials) the flankers pointed in the same direction as the target (compatible trial) and in the other 55% of the trials (660 trials) in the opposite direction (incompatible trial). Compatible and incompatible trials appeared in randomized order. Participants were instructed to respond with maximal speed and accuracy to the target arrow. The target arrow pointing to the left required a left-hand response and the target arrow pointing to the right required a right-hand response. Additionally, members of the correction-instructed group were instructed to correct any errors they detected. Each response was followed by a symbolic feedback (600 ms) about response speed, informing participants whether their answer was fast enough or should be speeded up. After the feedback a fixation cross was presented for 500 ms, such that the intertrial interval amounted to 2580 ms.

We introduced an adaptive algorithm, which dynamically adjusted the response time pressure based on the participant's performance. The algorithm aimed at an optimization of error rate (goal: 20% incompatible errors) and late response rates (as low as possible). This procedure helped to reduce drop-outs for a low number of error trials. The mean response deadlines were comparable between the noninstructed group (M = 434 ms, SEM = 13) and the correction-instructed group (M = 444 ms, SEM = 9), t(38) = -0.6, p > .58.

Psychophysiological Recording

The participants were seated comfortably in a dimly lit, electrically shielded chamber. The electroencephalogram (EEG) was recorded with Ag/AgCl electrodes from 51 electrode sites (the extended 10–20 system) referenced to left mastoid and off-line rereferenced to linked mastoids. Electrode impedance was kept below 5 k Ω . The vertical electrooculogram (EOG) was recorded from electrodes placed above and below the right eye. To monitor horizontal eye movements the EOG was collected from electrodes placed on the outer canthus of the left and right eye. EEG and EOG were recorded continuously with a low-pass filter of 70 Hz and AD converted with 22-bit resolution at a sampling rate of 250 Hz.

The ERP signals were response-locked averaged separately for incompatible correct and incompatible erroneous trials starting 100 ms before the response and continuing 600 ms postresponse. Compatible trials were excluded from statistical analyses, because of an insufficient number of error trials (<1%). Late responses (delivered after the response deadline) were also excluded from analyses. The average voltage in the 100 ms preceding the onset of the flanker arrows served as baseline. The single trial EEG signals were corrected for horizontal and vertical EOG artifacts by means of an eye movement correction procedure (Pfeifer, 1993) based on a linear regression method described by Gratton, Coles, and Donchin (1983).

In the response-locked averages, peak-to-peak measurements were calculated to determine baseline-independent amplitudes of negative deflections by subtracting the amplitude of the preceding positive peak from the subsequent negative peak of the components of interest. The time search windows of the ERN and the Pe were chosen a priori (cf. Falkenstein et al., 2000). For the ERN, two early time windows were defined from -80 ms to 0 ms for the positive peak preceding the ERN and from 0 ms to 120 ms for the ERN component. Because the Pe is a more sustained positive deflection, peak search was not possible in many participants' data. Therefore, the mean amplitude in the late time window from 300 ms to 500 ms was used for statistical analysis. To investigate the observed negative deflection following the ERN (see Results section), two middle time windows centered around this negativity were chosen post hoc: first, a time window from 100 ms to 180 ms for the positive peak preceding the negativity and, second, a time window from 120 ms to 300 ms for the negative deflection. Because this negativity only occurred on corrected error trials, peak search was not possible for uncorrected error trials. Therefore, the mean amplitude in the middle time window of 150–250 ms was used to compare corrected and uncorrected errors within the noninstructed group. The negative peaks in the early and middle time windows also served for obtaining latencies at the midline electrode FCz, where these deflections were maximal.

To avoid the loss of statistical power that occurs when repeated-measures ANOVAs are employed to quantify multichannel and multitime window data (Gevins et al., 1996; Oken & Chiappa, 1986), electrode sites were pooled to form six topographical regions. The following regions of interest were defined: left anterior (F5, FC3, FC5, C3), medial anterior (F3, Fz, F4, FCz), right anterior (F6, FC4, FC6, C4), left posterior (CP3, P5, P3, PO7), medial posterior (Pz, PO3, POz, PO4), and right posterior (CP4, P4, P6, PO8). For illustration purposes, a low-pass filter with a cutoff frequency of 15 Hz was applied.

Statistical Analyses

Response times were defined as the time between target onset and button press. Correction time was calculated as the response time difference between the erroneous and the subsequent corrective response.

The ERP statistics were based on a four-way repeated-measures ANOVA with the within-subject factors Response Type (two levels: correct and erroneous responses), Anterior-Posterior Dimension (two levels: anterior and posterior scalp regions), Lateral Dimension (three levels: right, middle, and left scalp region) and the between-subject factor Group (two levels: correction-instructed group and noninstructed group). Subsequently, lower order ANOVAs and t tests were computed to analyze resulting interactions. All effects with more than one degree of freedom in the numerator were adjusted for violations of sphericity according to the formula of Greenhouse and Geisser (1959). Reported effects revealed in lower order ANOVAs also reached significance using Bonferoni correction ($\alpha = .05/n$, where α is the probability of Type I error and *n* is the number of comparisons; Huberty & Morris, 1989). To avoid reporting large amounts of statistical results not relevant to the issues under investigation, only main effects or interactions including the Response Type, Correction Type, and Group factors are described. Scalp potential topographic maps were generated using a two-dimensional spherical spline interpolation (Perrin, Pernier, Bertrand, & Echallier, 1989) and a radial projection from Cz, which respects the length of the median arcs.

Results

Behavioral Data

As depicted in Table 1, typical effects of incompatibility were found for both reaction times and error rates. Correct response times, including in-time and late correct responses, and error rates were submitted to separate ANOVAs with the within-factor Compatibility and the between-factor Group. The analysis of correct response times revealed a significant main effect of Compatibility reflecting longer reaction times for incompatible correct trials than for compatible correct trials, F(1,38) = 1653.2, p < .0001. Error rates were higher for incompatible trials

	Noninstructed Group		Correction-Instructed Group	
	Compatible	Incompatible	Compatible	Incompatible
Correct	93.2 (1.5)	59.6 (1.4)	93.3 (1.4)	61.4 (1.0)
Error	0.7(0.2)	17.6 (1.2)	1.0 (0.2)	22.9 (1.9)
Correct late	4.7 (0.7)	20.9 (2.5)	5.1 (1.4)	15.1 (2.2)
Error late	0.2 (0.1)	0.5 (0.2)	0.2 (0.03)	0.2 (0.04)
Correct	305 (5)	369 (5)	302 (5)	368 (5)
Error	*	270 (4)	*	265 (3)
Correct late	447 (14)	438 (12)	455 (14)	437 (9)
Error late	*	*	*	*

Table 1. Mean Proportion and Reaction Times of Correct, Erroneous, and Late Responses for Each

 Stimulus Type

Notes: upper rows: response rates in percent; lower rows: reaction times in milliseconds. Standard error of the mean is presented in parentheses.

*Too few trials for meaningful analyses.

compared to compatible trials, F(1,38) = 973.9, $p < .0001.^{1}$ In addition, the noninstructed group showed lower error rates, F(1,38) = 5.4, p < .05, and a higher number of late responses, F(1,38) = 4.7, p < .05, compared to the correction-instructed group, suggesting a more cautious response behavior. Finally, an ANOVA with the within-factor Response Type (correct vs. erroneous) and the between-factor Group was performed for response times on incompatible trials. Consistent with previous findings, participants were faster on incompatible erroneous trials than on incompatible correct trials, F(1,38) = 1909.6, p < .0001.

To test whether performance on the trial immediately following an error differed between groups, we performed an ANOVA with the factors Previous Response Type (preceding correct vs. erroneous trial) and Group for dependent variables response time and error rate. The analysis of response time revealed a significant Previous Response Type \times Group interaction, F(1,38) = 8.1, p < .01. A subordinate within-group analysis showed a significant main effect of the factor Previous Response Type only in the noninstructed group, indicating longer reaction times of correct trials after errors (M = 390 ms, SEM = 6) than after correct responses (M = 382 ms, SEM = 6), F(1,19) = 8.9, $p < .01.^2$ The analysis of error rates also revealed a significant Previous Response Type \times Group interaction, F(1,38) = 11.1, p < .01, which was due to the fact that the noninstructed group produced more errors after erroneous responses (M = 18%, SEM = 2) than after correct responses (M = 13%, SEM = 1), whereas no such effect was present in the correction-instructed group (M = 19 vs. 19%).

Corrective Behavior

Participants in the correction-instructed group corrected their errors significantly more often (M = 96%, SEM = 1) than participants in the noninstructed group (M = 18%, SEM = 3), t(38) = 7.3, p < .0001. The mean correction time of 109 ms

(SEM = 8) for the noninstructed group and of 200 ms (SEM = 13) for the correction-instructed group differed significantly, t(38) = -6.0, p < .0001.

Corrective behavior varied depending on the reaction times for erroneous responses. Figure 1A illustrates the percentage of corrected errors sorted into the reaction time quartiles of erroneous responses. These data were subjected to an ANOVA with the factors Quartile and Group revealing a significant interaction between these two factors, F(3,78) = 29.7, p < .0001, $\varepsilon = .66$. This result suggests a different distribution of corrective behavior across reaction time quartiles. A subsequent within-group comparison showed an equivalent number of corrected errors within each quartile in the correction-instructed group, F(3,39) = 1.4, p = .27, $\varepsilon = .50$, whereas the percentage of corrected errors significantly differed among the quartiles in the noninstructed group, F(3,39) = 37.5, p < .0001, $\varepsilon = .70$. As illustrated in Figure 1A, the slower the reaction time for erroneous responses the larger was the percentage of corrected errors in the noninstructed group.

In addition, Figure 1A depicts the correction time for each error response time bin in the correction-instructed group (dotted line) showing that correction times decreased when error response time increased, resulting in a main effect of Quartile, F(3,39) = 13.7, p < .0001, $\varepsilon = .69$. An analogous analysis was not possible for the noninstructed group due to an insufficient number of trials available. However, it appears that correction times associated with longest error response times (quartile 4) in the correction-instructed group (174 ms) were nearest to mean correction times in the noninstructed group (109 ms). Thus, it seems that fast corrections in the correction-instructed group were most comparable to incidental error corrections in the correction-instructed group.

This impression is further supported by the distribution of corrective responses across correction times in bins of 50 ms as depicted in Figure 1B. As reported above, there were more corrections in the correction-instructed group than in the noninstructed group across all correction time bins, F(14,364) = 21.3, p < .0001, $\varepsilon = .22$. Incidental corrections in the noninstructed group fell mostly into the fastest correction time bins of the histogram whereas error corrections in the correction-instructed group showed mostly corrections in the slower correction time bins. The results suggest that the gain in error corrections in the corrections in the corrections in the slower corrections in the corrections in the slower corrections in the correction show error corrections. A large proportion of fast corrections seems to be independent of the intention to correct errors,

¹Response rate data were also tested after arcsine transformation. This and all subsequently reported statistical effects also reached significance by applying converted data to the ANOVA. The conversion was performed as follows: $X = \arcsin\left(\sqrt{Y/100}\right)$. X indicates the normalized value; Y indicates the percentage value.

²Trials preceded by compatible trials were excluded from analysis of post-error adjustments so that the comparison was between trials preceded by incompatible hits and incompatible errors. This procedure rules out confounds with the conflict sequence effect often observed in flanker tasks (Gratton, Coles, & Donchin, 1992).



out comparing incompatible noncorrected error trials and incompatible corrected error trials only within the noninstructed group. Fourteen participants (8 female) of this group had enough artifact-free corrected error trials to be included in the analysis. The time course of the response-locked ERP data for incompatible erroneous trials with and without correction is depicted in Figure 2 (solid lines). Compatible trials were excluded from statistical analyses, because of an insufficient number of error trials (<1%).

K. Fiehler, M. Ullsperger, and D.Y. von Cramon

Early time window (0–120 ms). A three-way ANOVA with the factors Correction Type (incompatible noncorrected and incompatible corrected error trials), Lateral Dimension, and Anterior-Posterior Dimension was conducted revealing no significant difference of ERN amplitude between corrected and noncorrected errors, F(1,13) = 0.2, p = .68. Latency analysis demonstrated a later peak of the ERN for noncorrected errors than for corrected errors (15 ms difference), t(13) = -4.3, p < .001.



instructed group and the noninstructed group. The dashed line shows correction time (time between erroneous/first and corrective/second responses) as a function of error response time in the correction-instructed group. Q1-Q4 refer to the ascending RT quartile score of erroneous responses calculated separately for the two groups. B: Distributional analysis of error corrections across 50-ms bins of correction times. The y-axis shows the mean number of error corrections; the x-axis shows 15 correction time bins.

Figure 1. A: Quartile analysis of error response times. Solid lines depict correction rate as a function of error response time for both the correction-

Correction-instructed group

whereas the majority of slow corrections results from the instruction for error correction. Therefore, ERP data were analyzed separately for fast and slow error corrections in the correction-instructed group.

ERP Data

Incidental Error Correction

Non-instructed group

As mentioned before, participants from the noninstructed group incidentally corrected almost one fifth of their errors, although corrective behavior was not instructed. To investigate

incidentally corrected (solid, black line) and uncorrected errors (solid, gray line) in the noninstructed group (N = 14) and for slow (dashed, gray line) and fast (dashed, black line) error corrections in the correctioninstructed group (N = 14) at FCz. In the upper part, topographical scalp distributions for the ERN (leftmost panel) and the CoRN (middle panel) for error corrections in the correction-instructed group, as well as the time window of the CoRN for uncorrected errors in the noninstructed group (rightmost panel), are depicted. ERN: error-related negativity, CoRN: correction-related negativity, Pe: error positivity.

Middle time window (150–250 ms). In the middle time window, there was a negative-going deflection exclusively occurring on corrected errors. In the mean amplitude analysis, a significant Correction Type × Lateral Dimension × Anterior-Posterior Dimension triple interaction was observed, F(2,26) = 4.5, p < .05, $\varepsilon = .94$, showing a smaller amplitude (i.e., a negativity) for corrected than noncorrected error trials at anterior electrodes, F(1,13) = 35.6, p < .0001. Because this negative-going deflection only occurred on corrected error trials we will henceforth refer to it as *correction-related negativity* (*CoRN*). As visible in Figure 2, both ERP waveforms, the ERN and the correction-related negativity, are fronto-centrally distributed.

Late time window (300–500 ms). To test for differences in Pe amplitude, repeated-measures ANOVAs were conducted revealing neither a significant main effect of the factor Correction Type, F(1,13) = 0.7, p = .43, nor any significant interactions with this factor.

Summing up the results, the latency of the ERN was significantly delayed for incidentally corrected errors relative to noncorrected errors, whereas ERN amplitude showed no differences. The ERN was followed by a fronto-centrally distributed negative deflection, which only occurred on error corrections, the correction-related negativity. The amplitude of the Pe did not differ between incidentally corrected and noncorrected errors.

Incidental versus Intentional Error Correction

Response time and correction time distribution analyses suggested a similarity of fast error corrections in the correctioninstructed group with incidental corrections in the noninstructed group (cf. Figure 1B). To disentangle different kinds of error corrections and to allow comparisons with the noninstructed group, corrected error trials were divided by the median of the correction time in each participant in the correction-instructed group. For subsequent comparisons between both groups and to rule out the influence of differences in error rates, we used a subsample of the correction-instructed group (N = 14; 6 female) whose error rates matched with the error rates of the noninstructed subgroup with a sufficient number of error corrections (as used for the within-group analysis reported above). For the correction-instructed group, the mean correction time for fast corrections amounted to 132 ms (SEM = 9) and for slow corrections to 274 ms (SEM = 17).

The response-locked ERPs for corrected and noncorrected errors in the noninstructed subgroup as well as for quickly and slowly corrected errors in the correction-instructed subgroup are illustrated in Figure 2.

Early time window (0–120 ms). To compare the amplitudes of the ERN for slowly and quickly corrected errors within the correction-instructed group, we conducted a three-way ANOVA with the within-subject factors Correction Speed, Lateral Dimension, and Anterior-Posterior Dimension. The analysis revealed no significant difference of ERN amplitude between slow and fast error corrections, F(1,13) = 1.1, p = .31. ERN peaked 20 ms later for slow as compared to fast corrections, t(13) = -5.3, p < .0001.

In a second step we contrasted amplitudes and peak latencies of the ERN of incidentally corrected errors in the noninstructed group with those of slow and fast corrections in the correctioninstructed group. Although inspection of the waveforms suggested larger ERN amplitudes in the noninstructed group, these differences did not reach statistical significance, Fs < 1.3, ps > .29. The ERN for corrected errors in the noninstructed group peaked earlier than for both quickly, t(26) = -2.1, p < .05 (latency difference = 7 ms) and slowly, t(26) = -7.2, p < .0001 (latency difference = 27 ms) corrected errors in the correction-instructed group.

Middle time window (120-300 ms). First, we contrasted the amplitudes of the correction-related negativity of incidentally corrected errors in the noninstructed group and quickly corrected errors in the correction-instructed group. The ANOVA with the factors Anterior-Posterior Dimension, Lateral Dimension, and Group revealed only a main effect of the factor Group, F(1,26) = 6.4, p < .05, reflecting a smaller correction-related negativity for incidental corrections in the noninstructed group compared to fast corrections in the correction-instructed group. The analogous analysis for incidentally corrected errors in the noninstructed group and slowly corrected errors in the correction-instructed group revealed again a main effect of the factor Group exhibiting a smaller correction-related negativity for incidental corrections in the noninstructed group compared to slow corrections in the correction-instructed group, F(1,26) = 4.7, p < .05. The within-group comparison for fast and slow corrections revealed neither a significant main effect, F(1,13) = 0.8, p = .40, nor a significant interaction of the factor Correction Speed.

Concerning latency analyses, the correction-related negativity in the correction-instructed group peaked earlier for fast corrections than for slow corrections, t(26) = -5.2, p < .001. Similarly, the correction-related negativity for incidental corrections in the noninstructed group peaked earlier than for slow correction in the correction-instructed group, t(26) = -3.4, p < .01, but at about the same time as for fast corrections in the correctioninstructed group, t(26) = -0.4, p = .46.

To examine whether the correction-related negativity is temporally dependent either on the first erroneous response or on the second corrective response, we computed an ERP image plot by using the software package EEGLAB (Delorme & Makeig, 2004). Figure 3A shows the ERN and the correction-related negativity components scaled to microvolt levels at channel FCz, aligned with the erroneous button press and sorted according to the participants' correction time. The ERP image plot demonstrates a distinct negative deflection in the time window of the ERN time-locked to the initial error. In the time window of the correction-related negativity, a negativity occurs after the corrective response and shows a distribution along the correction time.

Late time window (300–500 ms). The ANOVA testing for differences in Pe amplitude between fast and slow corrections in the correction-instructed group revealed a main effect of Correction Speed, F(1,13) = 33.0, p < .001, and two interactions, a Correction Speed × Anterior-Posterior Dimension interaction, F(1,13) = 5.2, p < .05, and a Correction Speed × Lateral Dimension interaction, F(2,26) = 8.1, p < .01, $\varepsilon = .83$. Follow-up contrasts suggested that these interactions reflect a larger positivity at frontal electrodes for fast error corrections.

Pe differences were also found in the between-group comparison of incidental corrections in the noninstructed group and fast corrections in the correction-instructed group, revealing a triple interaction Group × Anterior-Posterior Dimension × Lateral Dimension, F(2,52) = 6.0, p < .01, $\varepsilon = .92$. Follow-up



Figure 3. A: Response-locked ERP image plot for incompatible corrected error trials at channel FCz. Each vertically stacked thin color-coded horizontal bar represents a single trial in the event-related data set. Single trials are sorted according to the subjects' correction time (CT), smoothed across 50 neighboring trials in the sorting order, and plotted as a color-coded image. The trace below the ERP image shows the ERP average of the imaged data epochs. As data from all subjects of the correction-instructed group were collapsed, amplitudes of each trial were normalized for each subject. ERN: error-related negativity. B: Correct-response-locked and corrective-response-locked ERP averages, respectively, for incompatible correct trials (solid, black line) and incompatible corrected error trials (dashed, black line) for the correction-instructed group (N = 14) at channel FCz. C: Same ERPs as depicted in Figure 1B after 3.5 Hz high-pass filtering.

comparisons suggested that this difference is most pronounced at midline electrodes, particularly at frontal ones. Comparing incidental corrections in the noninstructed group and slow corrections in the correction-instructed group, a significant main effect of the factor Group was found, indicating a larger Pe for slow corrections in the correction-instructed group, F(1,26) = 12.6, p < .01.

To sum up the observed findings, the ERN peaked significantly earlier for incidentally corrected errors than for quickly and slowly corrected errors, whereas ERN amplitude showed no differences between these conditions. The correction-related negativity occurred on incidentally corrected error trials as well as quickly and slowly corrected error trials. This deflection was fronto-centrally distributed and time-locked to the corrective response. The amplitude of the correction-related negativity was smallest for incidental corrections and did not differ between fast and slow corrections. Whereas the correction-related negativity of incidentally corrected and quickly corrected errors peaked at about the same time, slow corrections were significantly delayed relative to the other two conditions. At frontal electrode sites, Pe amplitude significantly differed between incidental, fast, and slow corrections.

Discussion

The present data provide a number of new findings regarding immediate error corrections and related ERP phenomena. First, we discuss the behavioral findings. Second, we will focus on the observed negative deflection associated with immediate error correction, the correction-related negativity, and we will offer preliminary suggestions about its functional role. Third, the temporal characteristics of the ERN depending on error correction will be discussed. Finally, the results of ERN amplitude and the Pe will be elaborated within the framework of current models of performance monitoring.

Corrective Behavior

Consistent with previous findings, participants who were instructed to correct errors were able to do so very efficiently without being given an external signal that indicates a committed error (Higgins & Angel, 1970; Rabbitt, 1966a, 1966b, 1967). In line with the results by Rabbitt (1967), participants in the noninstructed group also showed immediate error corrections although to a lesser degree. These incidental corrections in the noninstructed group appeared in a similar time range as fast corrections in the correction-instructed group. The distributional analysis of correction times across response time quartiles of the erroneous responses showed that incidental corrections in the noninstructed group occurred mostly for slower errors. Similarly, fast error corrections in the correction-instructed group also occurred predominantly for slower errors; however, slow error corrections followed fast errors. These findings suggest that fast error corrections in the correction-instructed group are comparable to the incidental corrections in the noninstructed group.

In the following, the error correction behavior will be discussed in terms of the response conflict theory, which assumes that response conflict arises when more than one response tendencies compete (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Carter et al., 1998; Yeung, Botvinick, & Cohen, 2004). The short correction times for incidental corrections in the noninstructed group and for fast corrections in the correction-instructed group support the notion that these fast corrections occur when the correct response tendency very closely follows the erroneous one. Slow error corrections in the correct response tendency, which leads to a larger time span between the correct and the erroneous response tendencies. The time span can be modulated by the occurrence of the erroneous response tendency. Fast errors are associated with an early erroneous response tendency resulting in a large time span to the correct response tendency. Slower errors, however, are associated with a late erroneous response tendency leading to a shorter time span to the correct response tendency. The result that incidental corrections in the noninstructed group occured predominantly for slower errors suggests that only during slow errors is the immediately following correct response tendency executed, even when no corrective behavior was instructed. In contrast, during fast errors the correct response tendency seems not to be executed in the majority of trials in the noninstructed group. Either the correct response tendency does not further evolve because stimulus processing is finished or its execution is blocked as soon as an efference copy of the first response has been received. This seems to be changed by the intention to correct errors, such that also late corrections become possible. The initiation of slow error correction can either be due to a general prolongation of stimulus processing after the first response and/or a change in the response mode of the motor system allowing multiple responses.

Besides this continuous stimulus processing account, one could also assume a phasic intentional process triggered by error detection that actively enhances the evolving correct response tendency. The fact that intentional "error signaling responses" reported by Rabbitt (2002) were much slower than slow error corrections revealed in the present study: 650-750 ms compared to ~ 240 ms (correction time in the fastest error RT quartile) seems to question this account. It is important to note, however, that the intention to produce an error signaling response in Rabbitt's task requires leaving the current task set to recode the responses and to establish a new response tendency. In contrast, intentional corrections in the present study merely require that the existing correct response tendency is enhanced to exceed response threshold. It seems conceivable that this enhancement is less time consuming than the generation of a new response.

As mentioned above, error correction rate was modulated by experimental instructions. Moreover, response strategy seems to be affected by the possibility to correct errors. Participants who were unaware that error corrections were recorded showed fewer errors, more late responses as well as a reaction time slowing after an error suggesting a more cautious response behavior. Ridderinkhof (2002) suggested that the degree of cautiousness or impulsivity in task performance depends on the circumstances. It seems that when participants are explicitly told to correct their errors they view errors as expected and more acceptable than participants in the noninstructed group, who presumably believe that errors are unacceptable. Consequently, participants in the noninstructed group make sure that the response is completely appropriate before its execution, resulting in lower error rates and increased late responses. In line with the findings by Rabbitt and Rodgers (1977), responses following erroneous responses on the preceding trial in the noninstructed group were not only slow, but also less accurate, a finding not observed for participants in the correction-instructed group.

The Correction-Related Negativity

Exclusively for corrected errors, the ERN was followed by a negative waveform that was associated with the behavioral corrective response. We referred to it as correction-related negativity. Both ERP waveforms, the ERN and the correction-related negativity, are distributed over frontal sites. The topography of the correction-related negativity is slightly broader than the scalp

distribution for the ERN. It extends to electrode sites covering premotor cortices.³ The correction-related negativity peaks in the time window from 200 to 240 ms after the onset of an incorrect response and has a peak-to-peak amplitude of about 5 μ Vat FCz. Despite the fact that the correction-related negativity was also visible in previous experiments revealing high correction rates (Dikman & Allen, 2000; Falkenstein et al., 1994, 1996), this is the first study explicitly reporting a negative waveform related to error correction. In previous studies of Falkenstein et al. (1994, 1996), a small correction-related negativity is visible after visual and auditory stimuli, suggesting that the correction-related negativity is not affected by stimulus modality.

It is unlikely that the correction-related negativity is elicited by the additional motor response reflecting a movement-related potential (MRP; Shibasaki, Barrett, Halliday, & Halliday, 1980; Vaughan, Costa, & Ritter, 1968) of the correcting key press rather than a cognitive process. Recently published data by Rodriguez-Fornells and Münte (2004) compared one-hand responses and two-hand responses in a two-choice reaction time task. The result revealed no additional negative deflection for the second motor response. In an experiment by Falkenstein et al. (1994), participants were asked to press the response key twice. The time delay between the successive key presses approximated the delay of the correction key press. The data showed that MRPs only affected later ERPs effects, which occur around 300 ms (the Pe range).

The presence of the correction-related negativity does not seem to be related to the intention to correct errors as it was found in incidental corrections in the noninstructed group as well as in fast and slow corrections in the correction-instructed group, but its topography and amplitude may be modulated by intention. The ERP image plot indicates that the correction-related negativity is time-locked to the second corrective response rather than to the initial error. This offers the interpretation that the correction-related negativity is just a correct response negativity (CRN), an ERN-like wave observed after correct responses in some studies (Ford, 1999; Vidal, Hasbroucq, Grapperon, & Bonnet, 2000). However, if the second corrective response elicits a CRN, this component should also occur after the response on correct trials. As depicted in Figure 3B no negative deflection follows the first correct response. This is statistically supported by a significant main effect of the factor Condition (incompatible correct trials vs. incompatible corrected error trials) in the time window from 0 to 120 ms in the correct-response-locked and corrective-response-locked ERP averages, respectively, F(1,13) = 13.7, p < .01. To rule out the differential influence of the stimulus-related P300 that might have masked the CRN on correct first responses, a high-pass filter with a cutoff frequency of 3.5 Hz was applied. As can be seen in Figure 3C, no CRN is visible on correct trials, whereas the correction-related negativity remained present for corrective responses, F(1,13) = 12.8, p < .01. This finding makes it unlikely that the CRN and the correction-related negativity are the same component.

Recently, it has been suggested that the ERN reflects a burst of theta activity synchronized to the erroneous response (Luu & Tucker, 2001; Yordanova & Kolev, 2004). One could speculate that the correction-related negativity reflects a prolongation of

³The correction-related negativity also showed a slight lateralization to the right. Analyses of error and correction rates revealed no differences for right- and left-handed responses, so that the reason for the slight lateralization remains unclear.

this synchronized oscillatory activity of the (pre)motor system. The ERP image plot is inconsistent with this view: If the correction-related negativity results from the same theta oscillation as the ERN, the two waveforms should show a parallel distribution in the ERP image plot. However, with increasing correction time, the two waveforms diverge, that is, the correction-related negativity is delayed relative to the ERN. This was confirmed by a time-frequency analysis.⁴

In sum, we conclude that the correction-related negativity is most likely associated with corrective behavior. We speculate that the correction-related negativity reflects an evaluative function of the (pre)motor system that is active in the time range of the corrective response. Studies on motor responses sustained in time (in the range of seconds) reported a movement monitoring potential (MMP; Slobounov, Johnston, Chiang, & Ray, 2002), a negativity showing a frontocentral topography similar to the correction-related negativity but a different time course. Although the conditions under which the MMP and the correctionrelated negativity occur differ to an extent precluding direct comparisons, it could be speculated that both components are involved in monitoring processes of the premotor system. This assumption is consistent with the latest findings using functional magnetic resonance imaging (fMRI). The data showed a larger activation for corrected than uncorrected errors in the RCZ as well as in motor-related brain areas comprising the supplementary motor area (SMA) and the pre-SMA (Fiehler et al., 2004). The correction-related negativity could be associated with ongoing stimulus-response mapping based on continued stimulus processing and/or an enhancement of the evolving corrective response; however, the timing pattern makes it unlikely that the correction-related negativity is directly related to response selection. It is hence an important task for future experiments to reveal its precise functional role.

The ERN Latency and Error Correction

As expected, an ERN was observed after erroneous responses and occured in the theta frequency range time-locked to the initial error. Taking the different theories of the ERN into account, the result pattern for ERN latencies can be explained in terms of the response conflict model (Botvinick et al., 2001; Carter et al., 1998; Yeung et al., 2004). Using computational models, Yeung et al. suggest that the ERN amplitude is related to the amount of post-response conflict, that is, a multiplicative measure of the activities of the executed and the still evolving competing response tendencies. According to this model, the ERN should peak at the time of maximal post-response conflict. The authors further assume that an error detection system could work on the basis of post-response conflict monitoring by integrating the information about conflict with the information that a response has been already issued. In the present study, the latency of the ERN was delayed by about 15 to 20 ms for uncorrected and slowly corrected errors as compared to incidental and fast corrections, respectively. This is in line with the notion that the maximal post-response conflict is postponed when the second response tendency is delayed (Yeung et al., 2004).

The present findings seem rather inconsistent with the mismatch hypothesis (Falkenstein et al., 1990; Gehring et al., 1993). This model interpreted the ERN as an error detection signal resulting from a mismatch between the representation of the intended action and the actually performed action. In an early paper, Falkenstein et al. (1991, p. 453) assumed that the ERN was "elicited at the moment of the completion of the response selection process," that is, after completion of stimulus processing, when both response representations are fully available. This should result in an ERN latency in the time range of the corrective response. Particularly in slow corrections this should have led to an ERN latency increase of more than 150 ms, in contrast to 15 to 20 ms as observed in the present study. A later version of the mismatch hypothesis suggests that the comparison process takes place when the efference copy of the performed response arrives and is not waiting "until all possible information about the appropriate response is available" (Coles, Scheffers, & Holroyd, 2001, p. 175). Following this view, no latency differences should have been predicted.

Latency findings similar to the present results were reported by Falkenstein et al. (1996). Surprisingly, the ERN latencies between fast and slow corrected errors did not differ in the study by Rodriguez-Fornells et al. (2002). This difference might be explained by the medians of the reaction time for fast and slow corrected errors in the study by Rodriguez-Fornells et al., which are temporally closer than in the present results (104 ms vs. 141 ms). Assuming that the latency difference of the ERN depends on correction speed, a decreasing temporal distance between fast und slow corrected errors should diminish the ERN latency difference. Furthermore, in the comparison of uncorrected and corrected errors performed by Rodriguez-Fornells et al. one could argue that the interdiction to correct an error may have led to inhibition stopping all further stimulus evaluation and response selection processes immediately after delivery of the response. This may explain why only short ERN latencies were found in the uncorrected condition in that study.

ERN Amplitude

Our results for ERN amplitudes showed no significant difference between corrected and noncorrected errors in the correction-instructed group and between fast and slow corrections in the noninstructed group. This is inconsistent with any of the current theories of the ERN. Whereas a study by Falkenstein et al. (1994) also revealed no difference in the amplitude of the ERN between corrected and uncorrected errors after visual stimuli, other previous studies (Falkenstein et al., 1996; Gehring et al., 1993; Rodriguez-Fornells et al., 2002) have reported amplitude differences as predicted by the conflict monitoring model (Botvinick et al., 2001; Yeung et al., 2004) and the mismatch theory put forward by Coles et al. (2001). It remains unclear why the relationship of ERN amplitude and error corrections shows this inconsistent pattern of results in the literature and in the present study.

⁴We conducted a wavelet analysis of a time window ranging from -400 to +600 ms in relation to the erroneous responses based on the single-trial epochs in the continuous EEG data of each subject (cf. Tallon-Boudry, Bertrand, Delpuech, & Permier, 1997). The analysis was carried out at FCz using a Morlet wavelet transform (wave number 5.03). Frequencies were sampled at 71 intervals between 1 and 60 Hz, that is, at 12 intervals per octave. An increase of synchronized as well as total theta power was found in the latency range of the ERN. The maxima were in uncorrected errors (noninstructed group) at a frequency of 5.6 Hz (SEM = 0.26) and latency of 66 ms (SEM = 7) for total and at 4.87 Hz (SEM = 0.31) and 57 ms (SEM = 10) for synchronized activity, and in corrected errors (correction-instructed group) at 6.4 Hz (SEM = 0.25) and 81 ms (SEM = 11) for total and at 5.5 Hz (SEM = 0.33) and 80 ms (SEM = 10) for synchronized activity. There was no significant difference in latencies of the theta activities between corrected and uncorrected errors either for total or for synchronized activity.

Inspection of the waveforms suggests a larger ERN in the noninstructed group independent of whether the error was corrected or not. This group difference reached significance when all errors were collapsed in each group, F(2,76) = 6.0, p < .05. As pointed out above, the groups seemed to differ with respect to the motivational significance of the errors, as the correction-instructed group appeared to believe that errors are to some degree acceptable. We therefore argue that this difference can explain ERN amplitude differences between groups (cf. Falkenstein et al., 1994; Gehring et al., 1993; Ullsperger & Szymanowski, 2004).

The Pe

The Pe did not differ significantly between corrected and uncorrected errors in the noninstructed group, suggesting that it is not modulated by incidental corrections. There was a difference between incidental and fast corrections as well as fast and slow corrections, however, mostly due to a larger positivity on fast error corrections at midfrontal electrodes. The functional significance of these findings is rather unclear, because the Pe is usually maximal at centro-parietal electrodes (Falkenstein, 2004; Falkenstein et al., 2000). Falkenstein et al. (1994) suggested that the Pe in corrected errors could be influenced by a late MRP. However, the fact that no Pe difference was observed between corrected and uncorrected errors within the noninstructed group renders this account unlikely. Furthermore, our Pe findings are not consistent with the notion that this component is associated with post-error slowing (Nieuwenhuis et al., 2001), as we found a smaller Pe for the noninstructed group showing post-error slowing as compared to the correction-instructed group, in which post-error slowing was absent. It is important to note that the Pe has a large variability across different individuals and different tasks such that the exact nature of this component still remains to be determined (Falkenstein, 2004; Falkenstein et al., 2000).

Conclusion

In the present study, we reported the characteristics of a previously unnoticed ERP waveform related to immediate error correction, which we call the correction-related negativity. The correction-related negativity was present on both intentional and incidental error corrections, and seems to be more closely timelocked to the corrective response than to the initial error. One could speculate that the correction-related negativity reflects evaluative functions of the (pre)motor system necessary for error corrections.

We observed a modulation of the ERN latency by the occurrence and temporal characteristics of immediate error correction, which is consistent with the response conflict model. The data suggest that quickly and incidentally corrected errors are delayed correct responses, which arise from further stimulus processing to be reflected by an early peak of the ERN. In contrast, slow error correction seems to be based on a delayed correct response tendency resulting in a later peak of the ERN.

The behavioral data showed that the intention to correct errors significantly increases the correction rate resulting mostly in slow error corrections. This gain in error correction is due to an additional intentional process. The present data, however, do not allow us to assess whether the intention to correct errors results in a prolongation of stimulus processing exceeding the first response or in a change in the response mode or in a phasic implementation of intentional corrections after an error has been detected.

The notion that error detection is not necessary for incidental correction bears one important implication for clinical studies of error processing. Spontaneous (incidental) error correction rate has been used as an additional measure for error detection abilities in patient groups (e.g., Gehring & Knight, 2000). To assess error detection, it seems to be better to investigate intentional error corrections by instructing patients prior to the experiment or by introducing an error-signaling response (cf. Rabbitt, 2002).

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