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Event-related brain potentials and error-related processing: An analysis of incorrect responses to go and no-go stimuli

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Abstract

Recent research has suggested that there is a component of the event-related brain potential, the error-related negativity (ERN), that is associated with error detection and remedial actions such as error inhibition, immediate error correction, or error compensation. The present experiment used a go/no-go task to define more precisely the functional significance of this component. In this task, an ERN was observed for incorrect responses on go trials (errors of choice) and for responses on no-go trials (errors of action). Because errors of action cannot be corrected immediately by executing another response, these results indicate that the process manifested by the ERN is not dependent on immediate error correction. Other aspects of the data converge in suggesting that the ERN process is more closely related to error detection and that the connections between detection and remedial actions may depend on the task situation.

Descriptors: Error-related processes, Go/no-go task, Event-related potentials, Error-related negativity (ERN), Errors of choice, Errors of action

Contemporary approaches to human information processing distinguish between executive control and elementary information processing activities (Logan, 1985). The idea of executive control derives from the observation that human behavior exhibits considerable flexibility. The exact configuration of elementary information-processing activities can vary with the specific goals to be accomplished, and the dynamics of the system can be adjusted depending on the particular situation (e.g., De Jong, 1995; Gratton, Coles, & Donchin, 1992; Logan, 1985).

Further evidence for the existence of executive control in human information processing can be derived from the fact that the behavior of the system appears to be monitored. There is evidence that deviations from the required performance are detected and that adjustments to the system are made to reduce, or eliminate, such deviations. The existence of monitoring processes is suggested, inter alia, by the study of the system's reaction to errors (Angel & Higgins, 1969; MacKay, 1987; Rabbitt, 1966). When errors occur, they are sometimes corrected and adjustments to the system may be made to reduce the likelihood of making errors in the future.

Detailed examination of these kinds of processes was recently made more likely by the discovery of a component of the event-related brain potential (ERP) that appears to be associated with error-related processing activities (Falkenstein, Hohnsbein, & Hoormann, 1991; Gehring, Goss, Coles, Meyer, & Donchin, 1993). This ERP component, labeled the error-related negativity (ERN) (Gehring et al., 1993) or NE (Falkenstein et al., 1991), is present as a sharp negative deflection when trials on which the subjects commit an error are averaged synchronously to the incorrect response, but this deflection is virtually absent in the average ERP waveforms for trials on which the subjects respond correctly. The ERN can have an amplitude as large as 10 μV, peaking about 150 ms after the onset of the electromyographic activity associated with the erroneous response.

The processing of errors must involve at least two distinct subprocesses (e.g., Levelt, 1989; MacKay, 1987; Rabbitt, 1967). First, there must be a system that is capable of detecting errors by comparing the outcome of perceptual or response-related processing activities to the desired ("correct") outcomes.[1] A dis-

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[1] We make no assumptions about the accessibility of this system to awareness (or consciousness). Furthermore, the present study was not designed to address this issue. However, subject self-reports (in the form of expletives) suggest that at least on some occasions they are aware of their errors.

crepancy between the actual outcome and a representation of the correct outcome defines an error. Second, the system must have available a set of correction mechanisms that it may deploy when detecting an error. These mechanisms may attempt to suppress erroneous behavior (inhibition) and/or to substitute the correct response for the error (immediate correction). The detection of an error may also activate compensation mechanisms that act to prevent errors from recurring. Similar mechanisms have been proposed by Kornblum, Hasbroucq, and Osman (1990) in their model of stimulus-response compatibility effects.

The psychophysiological evidence on hand is consistent with accounts that relate the ERN both to an error detection mechanism and to an error correction or error compensation mechanism. Thus, following Rabbitt's (e.g., 1966, 1978) work on error-related processing, Gehring et al. (1993) examined the relationship between ERN amplitude and three putative measures of error correction and compensation. Their results showed that the larger the amplitude of the ERN, the weaker the force with which the incorrect response was executed. Gehring et al. argued that the process manifested by the ERN is related to the operation of a mechanism of response inhibition that acts to suppress the incorrect response. Furthermore, the larger the ERN, the greater the probability that an incorrect response is followed immediately by a correct response. This observation is consistent with the idea of an immediate error correction system that attempts to "undo" an error by activating the correct response. Finally, the larger the ERN, the slower the reaction times on correct trials following error trials. This suggests the presence of an error compensation mechanism that makes strategic adjustments to response bias.

Although this evidence points to a relationship between the ERN and correction and compensation mechanisms, the data are also consistent with the hypothesis that the ERN manifests the activity of a mechanism of error detection. It is possible that the inhibition of the error, the subsequent production of the correct response, and the effort to avoid errors in the future are all the consequence of an error signal produced by an error detection mechanism. In this case, the degree to which these correction mechanisms are activated would depend on the magnitude of the error signal. Increases in ERN amplitude may, under this interpretation, signify a more active error detection mechanism. Further evidence for a link between the ERN and error detection comes from the finding of a direct relation between ERN amplitude and the emphasis given to errors in speed–accuracy trade-off experiments (Falkenstein et al., 1991; Gehring et al., 1993).

The present study was designed to explore further the functional significance of the ERN. First, we were interested in the generality of the ERN for different kinds of errors. Second, should we find an ERN for different kinds of errors, would the same relationship between ERN amplitude and measures of remedial action be obtained? We used a hybrid go/no-go choice reaction time paradigm in which subjects could make two kinds of errors: errors of choice (i.e., executing the incorrect response alternative on a go trial) and errors of action (i.e., executing a response on a no-go trial when the stimulus does not call for a response at all). The comparison between these two kinds of errors is also of interest because immediate error correction is possible when errors of choice are committed but is impossible following errors of action. Once a response has been executed on a trial that does not require a response, that error cannot be undone by any subsequent motor response. If, indeed, the ERN is associated with the activity of a mechanism of immediate error correction, then we should expect the ERN to be smaller (or absent) for errors of action than for errors of choice. For both errors of choice and errors of action in our hybrid go/no-go choice reaction time task, we also evaluated the relationship between the size of the ERN and the degree of error (error inhibition) and the subjects' future behavior (error compensation).[2]

A second aim of this study was to test further the idea that the ERN is associated with a mechanism of error detection. Gehring et al. (1993) showed that the ERN amplitude was largest when response accuracy was stressed, whereas the ERN amplitude was smallest when subjects were encouraged to respond quickly. This finding implies that the same error can be associated with ERNs of different magnitude depending on the implications of erroneous behavior in the context of specific task requirements. From a strategic point of view, an increasing stress on accurate performance may lead to an increase in the subjective importance of the error. This variation in subjective importance could modulate the sensitivity of the error detection process manifested by the ERN. In the present experiment, we examined the idea of subjective importance from a different perspective. Regardless of whether subjects are under a speed or accuracy bias, the subjective importance of an error may depend on the "magnitude" of that error, in our case, defined in terms of the force exerted on the response device relative to the force required to register a criterion overt response. Thus, we contrasted two conditions: an easy squeeze condition in which the force required to register a response was small and a hard squeeze condition in which the force criterion was high. In this way, we could compare the errors for which the force exceeded the criterion force level (complete errors) in the easy squeeze condition with the errors in the hard squeeze condition that were below this criterion (partial errors). Although these errors in the two squeeze force conditions would be produced with similar absolute amounts of force, the complete errors may be perceived as more important than the partial errors. In the context of task instructions (as supported by a bonus system), partial errors have no explicit adverse consequences, whereas complete errors constitute both a failure in performance and a reduction in the financial reward. Thus, if the ERN is related to an error detection process, and if this process signals the "meaning" of the error, then the ERN for these complete errors should be larger than that for the partial errors.

To summarize, we used a hybrid go/no-go choice reaction time paradigm to address two questions regarding the functional significance of the ERN. First, we compared response-synchronized average ERPs associated with two kinds of errors: errors of choice and errors of action. Similar amplitude ERNs for these two kinds of errors would constitute evidence against the idea that the ERN is associated with a process of immediate error correction and would suggest that the ERN is associated with error detection. Second, we compared the ERN obtained for complete squeeze errors in an easy squeeze condition with the ERN obtained for partial squeeze errors in a hard squeeze condition.

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[2]The labels *errors of choice* and *errors of action* are used to describe two different classes of incorrect actions; that is, respectively, errors that can and errors that cannot be immediately corrected by executing another overt motor response. The use of these different labels should not be taken to imply that the two kinds of errors are dissimilar in all other respects. Errors of action presumably involve an element of choice (to go or not to go).

The ERN for the first type of error should be larger than for the second type of error if the detection process manifested by the ERN is modulated by the magnitude of the error, defined by the relationship between the force of the error and the force criterion level for a reaction time response.

Methods

Subjects

Four male and four female students (mean age, 20 years and 2 months; mean level of education, 14.8 years) at the University of Illinois participated in the experiment. All subjects were right handed and had normal or corrected-to-normal vision. Informed consent was obtained before the experiment began. All subjects were paid $4.00 per hour and a bonus earned during the experiment.

Procedure

The subjects were seated comfortably in front of a CRT (Hewlett-Packard vector display, Model 1310A) in a dimly lit room. They performed a discrimination task in which one of four visual stimuli was presented on each trial. The stimuli consisted of an arrow (.17 × .17 degrees of visual angle) in the center of a rectangle (1.49 × 1.66 degrees). The arrow was presented at fixation, and it pointed either to the right or to the left, indicating the hand with which the subjects had to make a response. The rectangles were positioned with the long side in either the horizontal or the vertical dimension. The orientation of the rectangle indicated whether subjects had to respond (go stimulus) or had to withhold their response (no-go stimulus). Thus, there were four different types of stimuli in this hybrid go/no-go paradigm; that is, go left, go right, no-go "left" and no-go "right." Each of the four stimulus types were presented equally often and in random order. The stimuli were displayed for 100 ms with an interstimulus interval (ISI) of 1,400 ms, during which a central fixation point was present.

Subjects responded by using their left or right hand to squeeze one of two zero-displacement dynamometers that were connected to an amplifier system (Daytronic Linear Velocity Force Transducers, Model 152A, with Conditioner Amplifiers, Model 830A) (Kutas & Donchin, 1977). The voltage output of the amplifier was a linear function of the force applied to the dynamometers and thus provided a continuous measure of overt response activation. A criterion reaction time response was defined in terms of a force exerted on either dynamometer that exceeded either 5% (easy squeeze condition) or 25% (hard squeeze condition) of the subject's maximum voluntary squeeze force for a particular hand; these force values were established before the experiment began. A click was presented over a loudspeaker to help subjects develop and maintain an idea of the criterion force level. This feedback was only provided during the practice trials and during the first five trials of an experimental block. Pilot work with this hybrid go/no-go choice reaction time task revealed that it was difficult to get subjects to make sufficient numbers of choice and action errors. Thus, to ensure an overall level of 85 to 90% accuracy based on complete responses (i.e., responses that exceed the criterion force level for a reaction time), we stressed response speed and rewarded fast correct responses on go trials with 3¢ and subtracted 1¢ for erroneous responses. The criterion for a "fast" response was determined by examining the subject's response speed during practice. Subjects averaged about 30¢ per block of trials. To obtain a reasonable number of errors of action for analysis, we emphasized to the subjects the importance of using the arrow stimuli to prepare their responses. We also used "filler" blocks of trials in which the probability of go trials was increased from 50 to 80% to increase the probability of errors of action. The data from these filler blocks were not included in any of the analyses.

In both the hard squeeze and the easy squeeze conditions, subjects received 40 blocks of 80 trials. The first 10 blocks of trials were used for practice. There were short 2–3-min breaks between successive blocks. The electrodes were applied after the practice blocks, and a 10-min break was provided after each series of 10 blocks. We presented one filler block of trials after every two regular blocks of trials in which go and no-go stimuli occurred equally often. The hard squeeze and easy squeeze conditions were administered on two different days with the order of the presentation counterbalanced between subjects. The go/no-go assignment to the orientation of the rectangles was counterbalanced between subjects.

Recording

The electroencephalogram (EEG) was recorded with disposable Ag/AgCl electrodes from Fz, Cz, Pz, and the right mastoid (the international 10-20 system), and C3′ and C4′ (placed 1 cm anterior to C3 and C4, respectively), each electrode being referred to a left mastoid electrode. The electrooculogram (EOG) was recorded from electrodes placed above and below the right eye to monitor vertical eye movements and from electrodes placed on the outer canthus of the left and right eye to monitor horizontal eye movements. The electrode impedance for EEG and EOG electrodes was less than 5 KΩ. EOG and EEG amplifiers (Grass model 7P122) were set to a high-frequency cutoff of 35 Hz (3 dB/octave roll-off) and a time constant of 8 s. The electromyogram (EMG) was recorded from electrodes placed on the flexors of both the left and right forearm (Lippold, 1967). EMG signals (electrode impedance <15 KΩ) were rectified using Grass Model 7P3B preamplifiers (0.5 amplitude low-frequency cutoff at 1 Hz) and then integrated (full-wave rectification and a time-constant of .05 s). All signals (EEG, EOG, EMG, and dynamometer output) were sampled at 100 Hz for 1,500 ms starting 240 ms before stimulus presentation.

Data Analysis

The EEG signals were referred algebraically to linked mastoid electrodes. This was achieved by subtracting 50% of the activity recorded at the right mastoid electrode from the activity at each of the other electrode sites. The single trial EEG signals were corrected for EOG artifacts using the procedure described by Gratton, Coles, and Donchin (1983). Trials with amplifier saturation artifacts were discarded as were the first five trials of each block. The remaining trials were filtered using a low-pass digital filter with 39 points and a transition band from 8 to 10 Hz (see Farwell, Martinerie, Bashore, Rapp, & Goddard, 1993). A baseline, computed as the average signal activity across the 100 ms prior to stimulus onset, was subtracted for all single trials. The amplitude of the ERN was defined as the most negative value in a 250-ms wide window, whose left boundary was placed on the most positive point in a 160-ms wide window centered on the EMG onset. The time at which this value was measured was taken as the latency for the ERN. The amplitude and latency measures of the ERN were taken independently at Fz, Cz, C3′, and C4′, where the ERN was discernable in the individual-subject waveforms. The peak amplitude of the ERN was measured both in the average waveforms of each subject and in the ERPs on the single trials. The amplitude was defined relative to a 50-ms baseline before EMG onset. Because both kinds of amplitude measurements resulted in a similar pattern of results, we report the results from the single trial analyses. The mean of the single trial ERN amplitude values will not be equivalent to the amplitude of the ERN evident in average waveforms. The amplitude of the average will be reduced because of latency jitter in the timing of the peak of the ERN.

The subjects' overt responses were evaluated using the integrated EMG activity for the left and right forearms, together with the measures of squeeze force. EMG onset, squeeze onset, and reaction time were measured on every trial. A computer algorithm determined the onset latency of the EMG and squeeze activity associated with responses of both the left and right hand. First, we computed the standard deviation of the signal across all trials in a block for each sample point in the 100-ms prestimulus baseline. Pilot work suggested that a noise criterion defined as four times the 80th percentile of these standard deviations provided an acceptable cutoff between signal and noise. Second, the algorithm determined the maximum amplitude in a window (70–600 ms) that exceeded the noise criterion, and the latency of this sample point was taken as the peak latency of the response. Third, the algorithm started a backward search along the leading slope of the response deflection until it encountered the first sample point whose amplitude was below the noise criterion. Finally, from this point on, the backward search was continued to determine the last point before the slope changed direction. The latency of this point was taken as the onset latency of the response. Trials were discarded when the algorithm indicated that the interval between the onset and the peak latency was larger than 400 ms, and when squeeze onset preceded EMG onset.

The measures of EMG onset, squeeze onset, and reaction time were used to define four possible patterns of response activation for each hand separately: (a) no response (i.e., no EMG activity above the noise level), (b) EMG response (i.e., EMG activity but no squeeze activity larger than the noise level), (c) partial squeeze response (i.e., squeeze activity in addition to EMG activity but with squeeze force below the criterion force level for a reaction time), and (d) complete squeeze response (i.e., squeeze activity above the criterion force level). These four classes of responses were used for a graded response analysis (cf. Coles, Gratton, Bashore, Eriksen, & Donchin, 1985).

The responses to go and no-go stimuli were classified into several possible response types, 12 of which had a sufficient number of trials for analysis (Table 1). In contrast to standard analyses of complete responses and reaction time, we used EMG and EMG onset latency, more sensitive measures, to determine whether and how fast a response had been initiated on a particular trial (cf. Gratton, Coles, Sirevaag, Eriksen, & Donchin, 1988). Table 1 lists both correct go and no-go trials and incorrect go and no-go trials (errors of choice and action, respectively). Correct go trials (Response Types 1–3) were trials on which the EMG onset latency for the signaled (correct) hand was faster than the EMG onset latency for the nonsignaled (incorrect) hand. These correct responses were all associated with complete squeeze responses. There was no response activity on the incorrect side for Response Type 1, but there was incorrect EMG and incorrect partial squeeze activity for Response Types 2 and 3, respectively. Correct no-go trials (Response Type 7) were characterized by the absence of EMG activity on both sides.

Table 1. *Mean Percent Trials Across Subjects, Separately for Go and No-Go Trials, for Each Response Type: The Easy Squeeze and Hard Squeeze Conditions and the Mean of These Two Conditions*

Response type	Easy	Hard	*M*
Go trials			
1. Correct go and no incorrect response	50.8	43.6	47.2
2. Correct go and incorrect EMG response	35.7	29.3	32.5
3. Correct go and incorrect partial squeeze	4.1	14.4	9.3
4. Incorrect EMG response	3.5	2.8	3.2
5. Incorrect partial squeeze response	3.5	7.4	5.5
6. Incorrect complete squeeze response	2.3	2.8	2.5
No-go trials			
7. No response	67.1	66.1	66.6
8. EMG response for the signaled hand	5.1	5.6	5.4
9. Partial squeeze for the signaled hand	3.7	6.7	5.2
10. Complete squeeze for the signaled hand	9.6	4.3	7.0
11. EMG response for the nonsignaled hand	5.9	6.9	6.4
12. Response activation for both hands	8.5	10.3	9.4

Incorrect responses consisted of both partial and complete errors. For partial errors, squeeze activity fell short of the force criterion for a reaction time (EMG and partial squeeze responses), whereas for complete errors squeeze activity exceeded this criterion (complete squeeze responses). Errors of choice (Response Types 4–6) were go trials on which EMG onset latencies on the incorrect side were faster than on the correct side. All the incorrect responses were followed by a correct complete squeeze response. When subjects made errors on no-go trials, they used either the hand signaled by the arrow feature of the stimulus, or they used the other hand. We refer to errors of action involving the signaled hand as *ipsilateral* errors (Response Types 8–10) because they involve a response with the hand on the side of the body signaled by the arrow. Errors of action involving the nonsignaled hand are referred to as *contralateral* errors (Response Type 11). No-go trials on which both hands were used were referred to as *bilateral* errors of action (Response Type 12). To provide performance results comparable with those based on traditional measures of overt behavior, we also performed some analyses using speed and accuracy measures for which the squeeze force exceeded the criterion.

The data for approximately 8.5% of the total number of trials (3,200) were not subjected to any analysis. These trials included those associated with recording artifacts as well as trials for which the response latency data were anomalous. All analyses described below involved standard analyses of variance designs for repeated measures. Test results are reported when the p values were smaller than .05; Greenhouse–Geisser epsilon values are provided where appropriate.

Results and Discussion

Performance

Table 1 shows the distribution of the trials across the 12 response types that were defined on the basis of the amplitudes and latencies of response-related activity in the EMG and the squeeze force channels. Measures of EMG activity were used to determine the presence of a correct response on the go trials and the absence of muscle activity on the no-go trials. The errors of choice (i.e., responding with the "wrong" hand on go trials) and the errors of action (i.e., responding with either hand on no-go trials) were a mixture of partial and complete errors (see Methods for more details on graded response analysis). Based on a standard analysis of complete error responses (Response Types 6 and 10), the overall level of accuracy was 90.5%. Further, the difference in the overall level of accuracy for the go (97.5%) and the no-go trials (83.6%) could be predicted from the low discriminability of the rectangles in combination with a bias toward completing rather than withholding responses, an effect of the bonus system.

The requirement for a higher squeeze force did not significantly affect response accuracy according to the standard analysis of errors (for go trials: easy = 97.7%, hard = 97.2%; for no-go trials: easy = 81.8%, hard = 85.3%). However, the relative frequency of various kinds of partial errors (Response Types 4 and 5, 8 and 9) was influenced by the level of force required for a correct squeeze. In particular, when the force requirement was high, there was a larger percentage of more forceful errors. Consistent with the squeeze force requirements, subjects squeezed the correct dynamometer with less force in the easy squeeze (peak value: 268 A/D units) than in the hard squeeze condition (peak value: 403 A/D units) ($F[1,7] = 9.95$, $p < .016$, $MS_e = 7349$). However, the value for the easy squeeze condition indicates that subjects squeezed more forcefully than was necessary to register a criterion response.

Scrutiny of the overall percentages of the different kinds of errors of action (Response Types 8–12) reveals that those made with the hand signaled by the arrow in the stimulus (the ipsilateral and bilateral no-go errors) occurred more frequently than errors of action that were made with the opposite hand (the contralateral no-go errors) (27.0 and 6.4%, respectively). This result is consistent with the biases introduced by the instructions and the bonus system and the fact that the go/no-go discrimination was harder than the discrimination between the arrows.

Figure 1 shows the mean EMG onset latencies for the correct go trials, errors of choice, and errors of action. Several analyses of variance were performed on these data. In all these analyses, squeeze force condition was included as a factor, but in no case was this factor significant or involved in significant interactions with other factors. For example, the response latencies for the correct go trials (Response Type 1) were not significantly different for the easy squeeze (299 ms) and the hard squeeze (288 ms) conditions.

We compared EMG onset latencies for errors of choice (averaged across Response Types 4–6) with correct go trials (Response Type 1). Incorrect EMG activity on the trials with errors of choice (226 ms) was initiated earlier than correct EMG activity on the correct go trials (294 ms) ($F[1,7] = 49.1$, $p < .0002$, $MS_e = 726.3$). This difference in EMG onset latencies suggests that the errors of choice were fast guesses, a suggestion that is supported by the fact that these errors were always followed by a complete squeeze response with the correct hand (325 ms) and by the fact that there was no ambiguity in the arrow feature of the stimulus that could have misled subjects into activating the incorrect hand.

A similar analysis compared ipsilateral errors of action (averaged across Response Types 8–10) with errors of choice (Response Type 1). This analysis revealed that ipsilateral errors of action ($F[1,7] = 43.9$, $p < .0003$, $MS_e = 345.3$) were slower (270 ms) than errors of choice (226 ms). Given our suggestion that errors of choice are fast guesses, this result would imply that

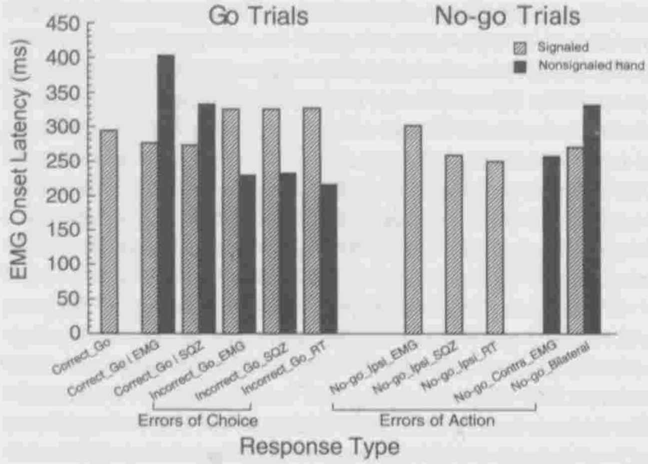

Figure 1. Mean EMG onset latencies across subjects for responses on correct go trials, on trials with errors of choice, and on trials with errors of action. The data are collapsed across the easy and the hard squeeze conditions. Correct_Go, correct go and no incorrect response; Correct_Go | EMG, correct go and incorrect EMG response; Correct_Go | SQZ, correct go and incorrect partial squeeze; Incorrect_Go_EMG, incorrect EMG response; Incorrect_Go_SQZ, incorrect partial squeeze response; Incorrect_Go_RT, incorrect complete squeeze response; Correct_No-go, no response; No-go_Ipsi_EMG, EMG response for the signaled hand; No-go_Ipsi_SQZ, partial squeeze for the signaled hand; No-go_Ipsi_RT, complete squeeze for the signaled hand; No-go_Contra_EMG, EMG response for the nonsignaled hand; No-go_Bilateral, response activation for both hands.

ipsilateral errors of action were not completely the result of guessing, a suggestion that is entirely consistent with the observation that when errors of action occurred, they were much more likely to be made with the hand that was indicated by the arrow feature in the stimulus display. When errors of action were made with the nonsignaled hand (Response Type 11), they were faster (259 ms) than comparable ipsilateral errors of action (Response Type 8; 301 ms) ($F[1,7] = 29.1$, $p < .001$, $MS_e = 490.7$). These contralateral errors of action were not significantly different from comparable errors of choice (Response Type 4; 231 ms) ($p = .067$). Thus, it appears that the contralateral errors of action, like the errors of choice, were more influenced by guessing processes than the ipsilateral errors of action.

These performance data demonstrate that the experimental manipulations produced errors of choice and errors of action. Errors of action were more frequent, reflecting the fact that the discrimination required to decide whether or not to respond was made deliberately more difficult. Furthermore, errors of choice appeared to be the result of guessing processes—these errors were fast and there was nothing in the arrow stimuli to lead the subjects to make an error. In contrast, errors of action appeared to be due to both guessing and a premature release of responses after an incomplete analysis of the stimuli. Because these errors occurred more often with the hand indicated by the arrow, they must have been the result of at least a partial analysis of the stimulus.

Error-Related Negativity

Matched and unmatched data. In the present experiment, we are concerned with (a) comparing response-synchronized average ERP waveforms for error trials with those for correct trials and (b) comparing ERP waveforms for errors of choice and errors of action. One problem with these kinds of comparisons is that they involve trials with different mean response latencies (see Figure 1). One consequence of this is that the motor responses are released at different times relative to the stimulus-related ERP activity. If response latency varies systematically between different conditions, any differences between response-synchronized waveforms for these different kinds of trials could be attributed to different contributions of the stimulus-related ERP activity overlapping the response-synchronized ERP activity (see also Gehring et al., 1993). Furthermore, the magnitude of the ERN may vary as a function of the amount of force with which the incorrect response is produced (Gehring et al., 1993). Thus, if there are different numbers of partial squeeze and complete squeeze errors for trials classified as errors of choice or errors of action, this difference could contribute to any observed difference in the ERNs between errors of choice and errors of action. For all these reasons, in evaluating some aspects of the ERN data, we selected for each subject subsets of the single-trial ERP waveforms to satisfy various matching criteria before we derived the response-synchronized averages.

We created for each subject three randomized sets of single trials comprising the correct go trials, the errors of choice, and the errors of action, respectively. From these three sets we selected trials that met three matching criteria. A first matching criterion involved response latency. Trials were selected such that their EMG onset latencies were within 10 ms of each other. A second matching criterion involved the magnitude of the incorrect response. Errors of choice were matched with errors of action of similar magnitude (e.g., Response Type 6 matches 10). Correct go trials were not subjected to this criterion, because all of them involved a complete squeeze response. A third matching criterion was the squeeze force condition. A selected triplet of trials came from either the easy squeeze or the hard squeeze condition. As we noted in the presentation of the performance results (Table 1), errors of choice were less frequent than errors of action. Therefore, the limiting factor in this selection process was the number of choice errors. It is evident from Table 2 that, after matching the data, the number of remaining trials was relatively small for Subjects 2 and 7. Hence, all analyses of matched data utilized data for the six subjects for whom there were at least 30 trials.

Is there an ERN for errors of action? Our first analysis was designed to determine whether, in our paradigm, there was an ERN for both errors of action and errors of choice. The identification of the ERN as a distinctive component associated with errors requires a comparison of the ERPs for incorrect trials with those for correct trials. Hence, we derived response-synchronized average ERP waveforms using the matched data for errors of choice (Response Types 5 and 6), errors of action (Response Types 9 and 10), and correct go trials (Response Type 1) with the response defined in terms of EMG onset. We only included partial and complete squeeze errors, because these kinds of errors have been the focus of previous work (Falkenstein, Hohnsbein, & Hoormann, 1995; Gehring, Coles, Meyer, & Donchin, 1995). Trials with only EMG errors are considered in subsequent analyses (see Figure 5).

As is evident from the ERP waveforms in Figure 2A and 2B, a negative-going deflection is elicited on partial and complete squeeze error trials whether the errors are errors of choice or errors of action. These negativities appear to start at about the time of onset of the "incorrect" EMG activity and peak about 160 ms later. In the case of errors of choice, "incorrect" EMG activity is activity in the hand that is not signaled by the arrow. In the case of errors of action, where any EMG activity is incorrect, the ERN is based on waveforms that are time synchronized to the first "incorrect" EMG activity that is evident after stimulus onset. For the ipsilateral errors of action, this incorrect activity is evident in the hand that is signaled by the arrow. In each case, the negativity has an anterior distribution, being larger at Fz and Cz than at posterior or lateral sites. These observations were confirmed by an analysis of variance (ANOVA) on the mean amplitude of the ERP waveform from 120 to 170 ms after EMG onset (response type: $F[2,10] = 6.38$, $p = .075$, $MS_e = 24.2$) and additional planned comparisons for errors of choice ($F[1,5] = 13.2$, $p = .015$, $MS_e = 78.8$) and errors of action ($F[1,5] = 8.2$, $p = .036$, $MS_e = 294.4$).

Because the morphology, the latency, and the scalp distribution of these negative ERP deflections were similar to those described for the ERN found for errors of choice in the two-choice reaction time paradigms (e.g., Falkenstein et al., 1995; Gehring et al., 1995), we infer that errors of choice and errors of action elicited an ERN in our go/no-go paradigm. Furthermore, the ERN associated with errors of action is similar to that reported by Falkenstein et al. (1995) (Figure 5) for their go/no-go paradigm. Because the average ERP waveforms for errors of action, unlike the waveforms for errors of choice, included only trials with a single motor response, the presence of an ERN for errors action argues against the idea that execution of a second (correct) motor response after an erroneous response (i.e., immediate error correction) is a necessary condition for the elicitation of the ERN.

The ERN and immediate error correction. The fact that the ERN occurred for errors of action indicates that activation of an immediate error correction process is not necessary for the elicitation of the ERN. Nevertheless, it could still be the case that an immediate correction process might contribute to the ERN. Indeed, Gehring et al. (1993) showed that the amplitude of the ERN was larger on those trials on which errors of choice were immediately corrected.

To explore further the role of such error correction, we made a direct comparison between the ERNs (measured on single trials) for errors of action and errors of choice. Because errors of choice are in principle correctable (and in fact they were always immediately corrected in our paradigm), any contribution of an

Table 2. *Matched Data: Number of Trials and Reaction Times (in ms) for Each Subject*

		Reaction times		
Subject	Number of trials	Correct go	Incorrect go	Incorrect no-go
1	42	235	230	233
2	18	264	261	264
3	58	223	218	221
4	41	218	214	217
5	93	210	206	210
6	87	221	217	221
7	12	276	277	278
8	39	241	237	241

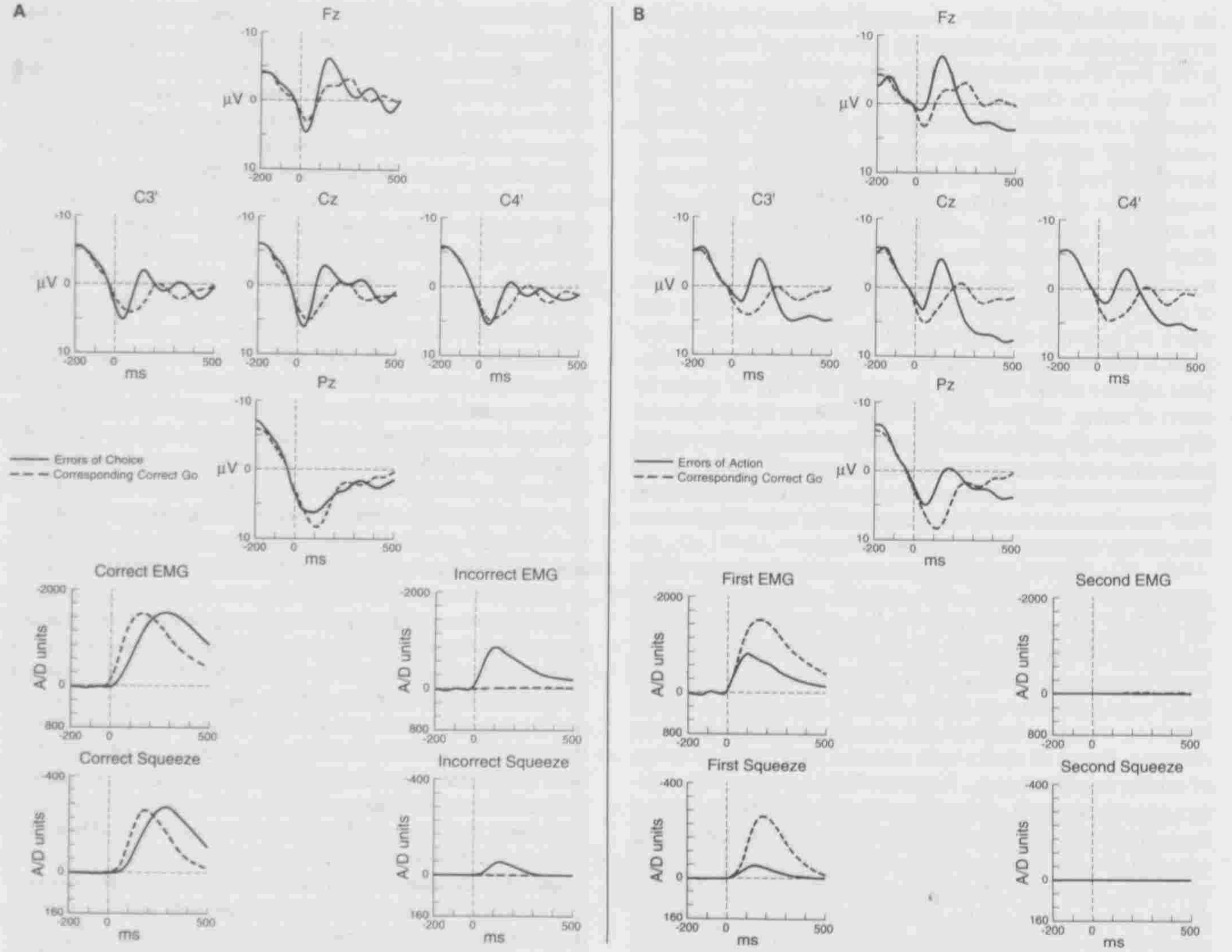

Figure 2. Grand-mean ERP waveforms across subjects at each electrode site. The single trial ERPs for each subject were response-synchronized and then averaged to yield an average ERP waveform. A. Trials with errors of choice are contrasted with a matched set of trials with correct go responses. B. Trials with errors of action are contrasted with the same matched set of trials with correct go responses. The details of the matching procedure are described in the text. Error trials consisted of partial and complete squeeze errors. Correct and incorrect EMG activity and squeeze force are also shown. For errors of choice, *incorrect EMG* activity refers to activity associated with the response that was not signaled by the arrow. For errors of action, *first EMG* refers to the EMG associated with the response that was made first following a no-go stimulus.

immediate error correction process to the amplitude of the ERN should be evident in this comparison. In fact, as Figure 3A shows for matched trials with partial and complete squeeze errors (Types 5, 6, 9, and 10), the ERN amplitude was not significantly larger for errors of choice than for errors of action (error type: $p = .94$, Error Type × Electrode: $p = .90$; $-13.6\ \mu V$ and $-13.5\ \mu V$, respectively).

To evaluate the effects of the matching procedure, we also conducted a similar analysis in which all trials with Response Types 5, 6, 9, and 10 were used in generating the averages. As Figure 3B shows, the waveforms for these unmatched data are similar to those shown in Figure 3A for the matched data. The difference between the ERN amplitudes for unmatched errors of choice and action was also not significant (error type: $p = .98$, Error Type × Electrode: $p = .67$; $-15.4\ \mu V$ and $-15.7\ \mu V$, respectively).

Taken together, the analyses for both the matched and unmatched data did not reveal significant differences in the ERN amplitude for errors of choice and errors of action. Because errors of choice always involved two responses (incorrect followed by correct), whereas errors of action involved only a single response, the data argue against the idea that the ERN for errors of choice is associated with the activity of a mechanism of immediate error correction.

The ERN and error inhibition. The idea that the ERN is associated with a mechanism of error inhibition that acts to suppress the incorrect response in two choice reaction time tasks was derived from the observation that the ERN amplitude was related inversely to the amount of squeeze force used for making the incorrect response (Gehring et al., 1993). Because it is not clear whether this relationship will generalize across different task sit-

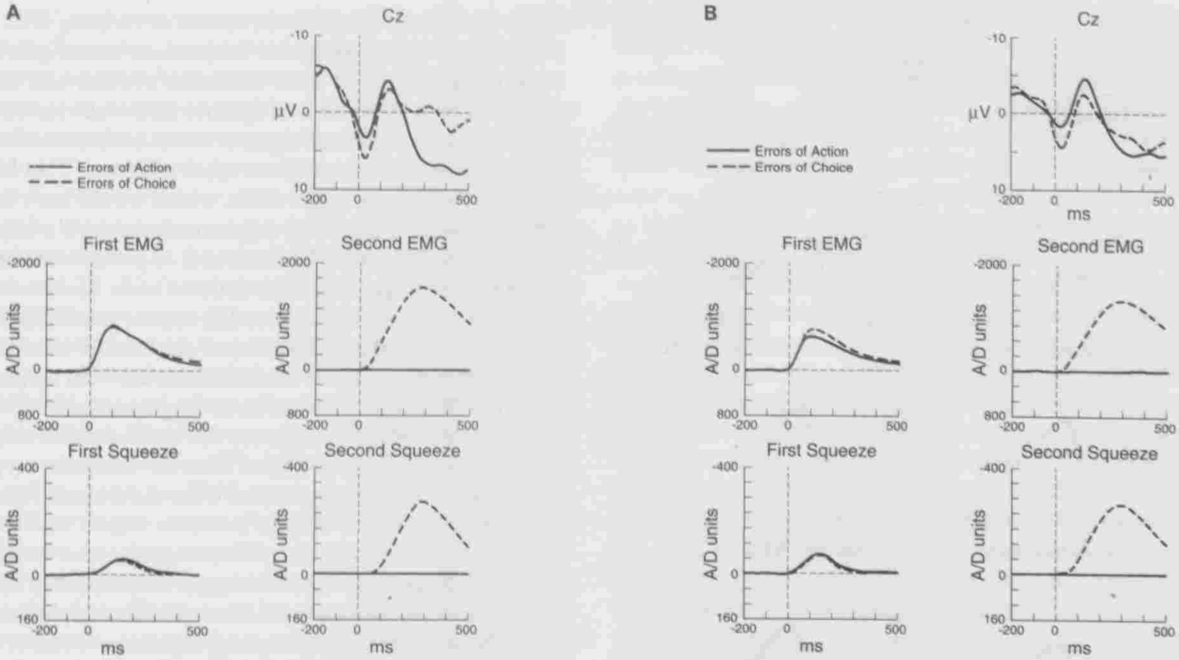

Figure 3. Grand-mean ERP waveforms (response-synchronized) at Cz for errors of action and errors of choice. A shows matched data, and B shows average ERP waveforms that included all partial and complete squeeze error trials. Traces for EMG activity and squeeze force are also shown. *First* refers to EMG activity that occurred first on a trial. For errors of action, any measurable response activation in either the left or right arm constituted an error. For errors of choice, *first* corresponds to response activation in the nonsignaled (incorrect) arm.

uations, we explored it further in the present hybrid go/no-go choice reaction time task. Using the logic of a "forward" analysis, we determined whether trials with large ERNs would have less forceful errors than trials with small ERNs. Hence, we used the ERN amplitude at Cz to divide the incorrect trials into quartiles, ranging from small to large ERNs. Subsequently, we computed mean squeeze force for each quartile. This procedure was applied to all partial and complete squeeze error trials for both go (Response Types 5 and 6) and no-go conditions (Response Types 9 and 10) from the six subjects whose data were included in the analyses of Figure 2A and 2B. It is evident from Figure 4 that the algorithm we used to classify error trials in terms of ERN amplitude was effective, because the portion of the waveform that discriminates between the different classifications corresponds to what we have defined as the ERN. The squeeze force traces in Figure 4 show that there was no significant decrease in squeeze force with increasing ERN amplitude (quartile: $p = .84$; Error Type: $p = .13$; Quartile × Error Type: $p = .77$).

We performed a similar ANOVA to that described earlier, but this time we included both EMG and squeeze errors (Response Types 4–6 and 8–10) from all subjects. Again, there were no significant differences in squeeze force as a function of ERN amplitude (quartile: $p = .47$; error type: $p = .36$; Quartile × Error Type: $p = .52$).

Finally, we performed an analysis in which we compared directly the ERNs obtained for EMG, partial squeeze, and complete squeeze errors. Specifically, we compared the ERNs across Response Types 3–5 for errors of choice and across Response Types 8–10 for the ipsilateral errors of action. As is evident from the traces for EMG and squeeze activity in Figure 5, the degree of error classification yielded the same pattern of results when applied to errors of choice and errors of action: the size of EMG, partial squeeze, and complete squeeze errors was very similar for the two types of error. Figure 5 also shows that the ERN was of similar magnitude for partial and complete squeeze errors, confirming the results of the forward analysis. However, the ERN amplitude for EMG errors was smaller than that for the two errors involving squeezes (degree of error: $F[2,14] = 13.2$, $p < .0006$, $MS_e = 91.2$, $\epsilon = 0.6848$). This result was confirmed by tests of specific contrasts on the degree of error factor. As Figure 5 suggests, there was no significant main effect of error type ($p = .75$) and the interaction of degree of error and error type was also not significant ($p = .27$).

Taken together, the data from our hybrid go/no-go choice reaction time task present a different picture of the relationship between the ERN amplitude and the degree of error than that derived from data obtained in a two-choice reaction time task (Gehring et al., 1993). For the analyses that correspond most closely to those conducted by Gehring et al. (involving partial and complete squeeze errors only), there was no relationship between error force and ERN amplitude. When EMG errors were also evaluated, the ERN was actually smaller for these errors than for squeeze errors. These results argue against the idea that the ERN is always associated with the activity of an inhibitory mechanism that acts to abort the incorrect response. In contrast, a small ERN for response errors at the level of EMG, together with a more pronounced ERN for partial and complete squeeze errors, is consistent with the alternative explanation that the ERN is related to the degree of error and may be associated with a mechanism of error detection. The detection mechanism could have two discrete states of activation (i.e., it detects the absence or presence of squeeze activity) but does not distinguish between partial and complete squeeze responses.

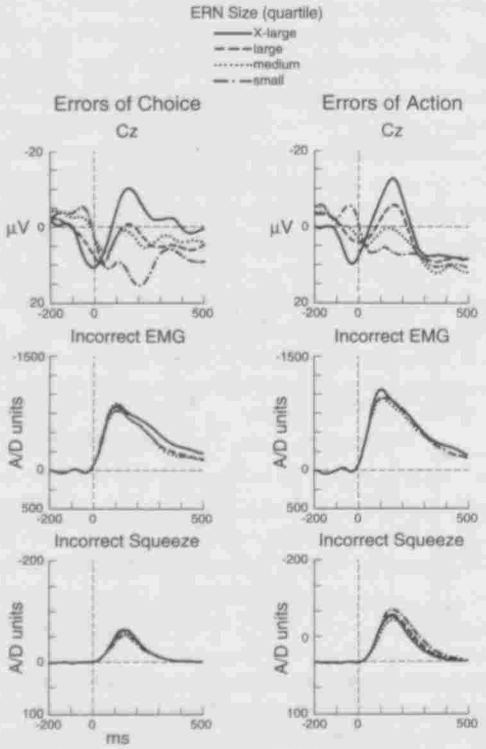

Figure 4. The results of the "forward" analysis of degree of error. Trials with partial and complete squeeze errors were divided into four quartiles based on the ERN amplitude. Average ERP waveforms (response synchronized), shown for Cz, were computed for each quartile. EMG and squeeze force traces are also shown. The analyses were performed separately for errors of choice (left) and ipsilateral errors of action (right). For errors of choice, *incorrect* refers to activity associated with the hand that was not signaled by the arrow. In the case of errors of action, *ipsilateral* refers to activity associated with the hand signaled by the arrow. Unlike the other figures, we did not subtract a 50-ms preresponse baseline.

To integrate the present findings and those of Gehring et al. (1993), it is necessary to consider several important differences between the two task situations. Gehring et al. used the Eriksen flankers task in which at least some errors of choice could be attributed to ambiguities in the stimulus. On some occasions, the visual array that served as the stimulus contained information in favor of both correct and incorrect responses. In these circumstances, errors could have arisen as a result of partial information about the distractors priming the incorrect response. Also, with ambiguous stimuli, the processing system may fail to derive a clear representation of the correct response. The lack of such a representation would hinder the error detection process and result in a small error signal. This kind of scenario would explain the co-occurrence of a forceful error and a small ERN. However, if information about both correct and incorrect responses was available at the time the error occurred, then the two responses would compete with each other, but the error detection process would have less difficulty making a comparison. In this case, the error would be smaller, but the ERN would be larger because of a stronger error signal.

The preceding reinterpretation of the Gehring et al. (1993) results attributes variation in the magnitude of the error to a response competition process rather than to an inhibitory process that is triggered as a result of error detection. However, it is also possible to integrate the results of Gehring et al. and the present study by assuming that subjects can reconfigure the relationship between their error detection systems and inhibition mechanisms as a function of specific task requirements. In the present task, it is evident that the detection mechanism is able to distinguish between different types of errors. This is because ipsilateral errors on no-go trials, which would have been correct responses on go trials, were associated with a large ERN. Thus, the system must have been able to use information about the kind of trial to define what counted as an incorrect response on that trial. However, it does not appear that inhibitory systems were invoked as a function of the kind of error detected, because of the absence of a relationship between the size of the ERN and the force of the incorrect response for both errors of action and choice. The reason for this disconnection may be that the inhibitory actions needed after error detection on go trials ("stop and go") are quite different from those needed after detection of a no-go error ("stop"). Evidence from a recent study of stopping (De Jong et al., 1995) suggests that stopping all responses, as in the no-go situation, is accomplished by a much more peripheral inhibitory mechanism than stopping and going (see also De Jong, Coles, Gratton, & Logan, 1990). It may not be possible for the system to hold both these kinds of inhibitory mechanisms simultaneously available for use. However, the correction system was clearly acting differently as a function of the kind of error detected. Although all errors of choice were followed by a correct response, only about 25% of the errors of action were associated with a double response.

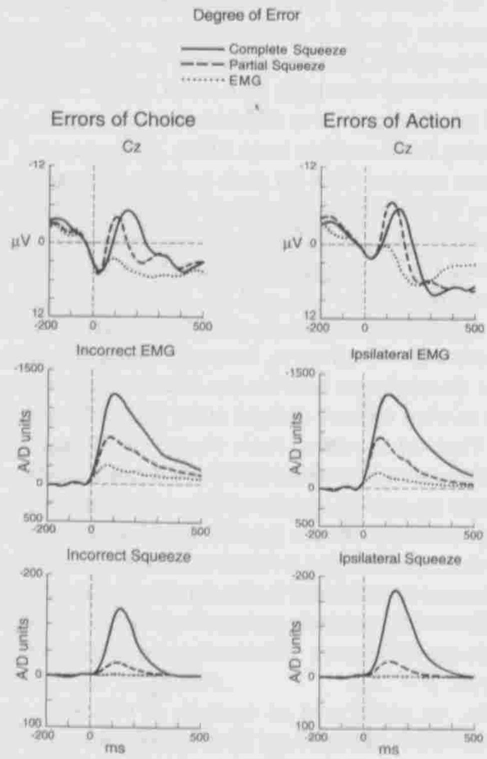

Figure 5. Grand-mean ERP waveforms (response synchronized) at Cz, for errors of choice (left) and ipsilateral errors of action (right) as a function of absolute squeeze force. For errors of choice, *incorrect* refers to activity associated with the hand that was not signaled by the arrow. In the case of errors of action, *ipsilateral* refers to activity associated with the hand signaled by the arrow.

The ERN and error compensation. The next analysis explored the idea that longer-term strategic adjustments are made after an error has been committed. We examined the EMG onset latencies on correct go trials as a function of whether the ERN on the preceding incorrect trial was smaller or larger than the median ERN amplitude for an individual subject. Because of the low frequency of error trials that were followed by correct go trials, the analyses used the data from the same six subjects who contributed to the matched waveforms presented in Figure 2A and 2B. We found that response speed after partial and complete squeeze errors (Response Types 5, 6, 9, and 10) did not depend significantly on the amplitude of the ERN ($p = .11$). This was true for both errors of choice (small ERN: 292 ms, large ERN: 301 ms) and errors of action (small ERN: 291 ms, large ERN: 302 ms). We also computed, for each individual subject, the correlation coefficient between the ERN amplitude on an incorrect trial and the EMG onset latency on the following trial when the trial was correct. For neither errors of choice nor errors of action was there a significant correlation for any of the subjects (the correlations ranged from −.05 to −.36 for errors of choice and from .01 to −.23 for errors of action).

We repeated the same analyses using EMG errors (Response Types 4, 8, and 11) and partial and complete squeeze errors. Response latency was longer after error trials with large ERNs relative to error trials with small ERNs ($p = .07$; for errors of choice: small ERN: 289 ms, large ERN: 297 ms; for errors of action: small ERN: 284 ms, large ERN: 304 ms). The correlations between the ERN amplitude and the EMG onset latency on the following correct go trial, computed for individual subjects, were all nonsignificant, ranging from .13 to −.29 for errors of choice and from .02 to −.21 for errors of action.

Taken together, these data indicate that, for both errors of choice and errors of action, the ERN amplitude was related (but not quite significantly) to a slowing in the response speed on the subsequent correct go trial. Despite the weakness of this relationship, it is important to note that its direction and magnitude were the same as observed previously (Gehring et al., 1993). This finding is consistent with the idea that the ERN is associated with an error detection process, a process that produces an error-signal that, in turn, triggers future compensatory behaviors.

The ERN and error detection. Thus far we have explored the idea that the ERN is associated with mechanisms of error correction and compensation. We have provided evidence to suggest that the ERN is not a direct manifestation of the activity of these kinds of mechanisms. Rather, the ERN appears to be a manifestation of error detection. We argued earlier that an error detection system operates by monitoring the outcome of perceptual or response-related processing activities. The system presumably involves a comparison process that computes the degree of mismatch between the actual outcome and the intended or correct outcome. If this computation involves representations of the erroneous response, then the ERN amplitude should increase with larger errors. We observed earlier that, consistent with this idea, the ERN differentiated between EMG errors, on the one hand, and partial and complete squeeze errors, on the other. However, the ERN did not differentiate between partial and complete squeeze errors, errors that also differed in terms of absolute force.

We mentioned earlier that, in the Gehring et al. (1993) experiment, the ERN amplitude for errors made with the same absolute amount of force depended on whether the error was made under speed, neutral, or accuracy instructions. This implies that the ERN may be modulated by the perceived importance of the error in the context of task requirements. In the present study, the squeeze force manipulation was included so that we could determine whether the meaning of a response of a particular force was related to the amplitude of the ERN. By *meaning*, we refer to the status of a response of a particular force in relation to the force criterion level for a reaction time response.

For errors of choice (Response Types 5 and 6) and ipsilateral errors of action (Response Types 9 and 10), we compared partial squeeze errors from the hard squeeze condition with complete squeeze errors from the easy squeeze condition. These errors were executed with similar force, but they differed in terms of whether the squeeze activity did or did not exceed the force criterion; that is, whether the error was partial or complete. The relevant data are presented in Figure 6. In fact, the ERN amplitude was not significantly different for partial and complete incorrect responses (−14.9 μV and −15.9 μV, respectively; $p = .46$). Thus, if the ERN is associated with an error detection mechanism in this task, then this mechanism is insensitive to differences in the relative magnitude of the error as defined by the force criterion.

What are the reasons for this insensitivity? The most obvious is that the subjects had a rather imprecise representation of the objective threshold between partial and complete squeezes. Feedback relating to the force criterion was only provided during training and during the first five trials of each experimental run. Subjects did not receive feedback on the trials used in the previous analysis and thus had to rely on memory for the force requirements associated with the execution of the correct

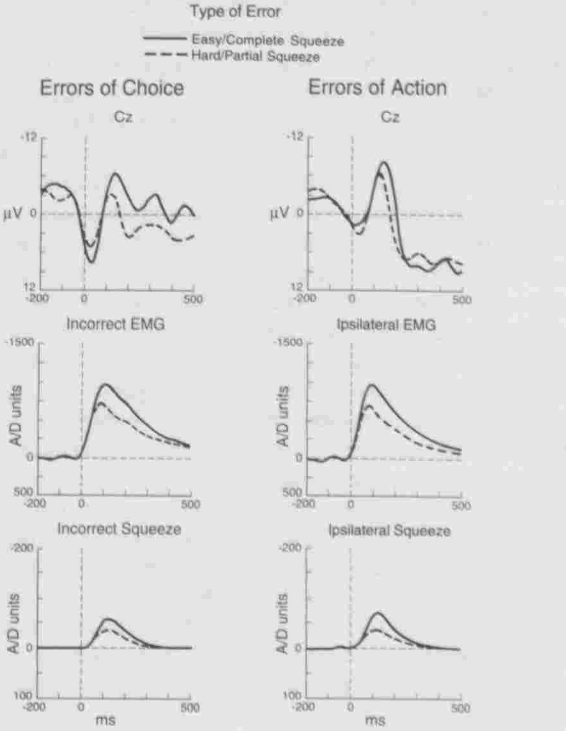

Figure 6. Grand-mean ERP waveforms (response synchronized) at Cz for error responses of similar absolute force in the easy and hard squeeze conditions. The ERN data and related EMG and squeeze activity are shown for errors of choice (left) and ipsilateral errors of action (right). *Incorrect* and *ipsilateral* have the same meaning as in previous figures.

response. This would also explain why the difference in the actual force associated with correct responses in the easy squeeze and the hard squeeze conditions was smaller than the difference in required force (see the section on performance results). A consequence of the imprecise representation of the criterion squeeze force would be that partial and complete errors carried the same meaning.

Another possible reason for the insensitivity may lie in the nature of the go/no-go task itself. Because no response was required on 50% of the trials, the critical response parameter for the evaluation of an error was whether any force was exerted on the response device and not how much force was exerted. This inference is supported by the fact the ERN was much smaller for EMG errors than for squeeze errors (see Figure 5).

Finally, under the speed instructions of the present experiment, the error detection process should be relatively insensitive (and the average amplitude of the ERN would be correspondingly small; cf. Gehring et al., 1993). In this case, differences in the meaning of errors with different force values would be less detectable than if the system was adjusted to be more sensitive (e.g. under accurate instructions). This would be particularly true if the function relating subjective importance to error force was a negatively accelerating function, with an asymptote at a level of importance associated with a force level below the criterion for a reaction time response. In this regard, it should be noted that within the easy and hard conditions, there were no differences in ERN amplitude between partial and complete errrors.

Conclusions

The ERP data obtained with our hybrid go/no-go choice reaction time task show clearly that the ERN is elicited by both errors of choice and errors of action in a similar fashion as by incorrect responses in two-choice reaction time paradigms (Falkenstein et al., 1991, 1995; Gehring et al., 1993, 1995). Falkenstein et al. (1995) also recently provided evidence of an ERN (or NE) on "false alarm" trials of a standard go/no-go task requiring responses with one hand (see their Figure 5). Together, the data indicate the generality of the ERN as a manifestation of error-related processing. In contrast with the results from the two-choice reaction time paradigms, the present data point to a dissociation between the process manifested by the ERN and those involved with error inhibition and correction. First, the absence of a reduction in the ERN amplitude for the errors of action relative to the errors of choice suggests that there is no effect of the correctability of the error. Whereas it is impossible to "undo" an incorrect response on a no-go trial by making a second motor response, incorrect responses on go trials were always corrected (immediate error correction). However, this difference in the correction process was clearly not reflected in a difference in ERN amplitude. Falkenstein et al. (1995) also claimed that the presence of an ERN for false alarms in their standard go/no-go task provided evidence for the independence of the process associated with the ERN from error correction activity. Second, our data do not support the idea that the ERN is associated directly with a mechanism of error inhibition. In contrast with the inverse relationship between ERN amplitude and error force reported by Gehring et al. (1993, 1995), our data show that the ERN amplitudes for trials with partial and complete squeeze errors were not significantly different. It is always difficult to draw strong conclusions about null results. However, the present failures to find a reduction in ERN amplitude as a function of the immediate correctability of the error and to observe consistency in the relationship between the ERN amplitude and behavioral measures of error inhibition across different types of tasks suggest that the process manifested by the ERN is not directly concerned with these kinds of error-related processes.

We found a weak link between the ERN and error compensation. The response latencies for correct go trials following errors of choice and errors of action were longer for trials with large ERNs. Although these effects were not quite statistically reliable, they were of the same magnitude as those reported by Gehring et al. (1993).

Taken together, our results are most readily explained by assuming that the ERN is associated with an error detection process. As we argued earlier, this system must be able to detect errors by monitoring the outcome of perceptual or response-related processing activities and subsequently comparing this information with the correct or intended outcome. Variation in the amplitude of the ERN reflects the degree to which the error detection process has recognized the error. The ERN process can be influenced further by the implications of erroneous behavior in the context of specific task requirements.

Flexibility appears to be a fundamental characteristic of human information processing (cf. Logan, 1985). This principle also appears to apply to the way in which the error detection process is set up. For example, in the present experiment, the detection process appears to be sensitive to two error states: a small flag for EMG-only errors and a large one for errors involving some kind of squeeze activity. The detection process did not appear to be sensitive to variation in the meaning of errors of different absolute force levels. In addition to flexibility in the rules for detecting and evaluating a response as an error, there is also flexibility in the connection between the detection system and the inhibition, immediate correction, and compensation systems discussed earlier. The precise nature of the link will depend on the task situation. In this case, the detection system was not coupled directly with inhibition processes and its coupling with immediate correction processes was dependent on the type of error (choice or action). Apparently, the degree to which these remedial actions were taken depended on some other processes that categorized the error. However, the detection system did seem to be connected to a compensation system.

Contemporary theories of human information processing are beginning to consider the role of executive control and monitoring operations. Although the ERN does not provide a complete picture of the operation and timing of these monitoring activities, it does promise to reveal important insights into what happens when the monitoring process detects a deviation between actions and intentions.

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