Action monitoring in motor control: ERPs following selection and execution errors in a force production task

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Abstract
Action monitoring has been studied in many tasks by means of measuring the error-related negativity (Ne/ERN), but never in a motor control task requiring precise force production. Errors in discrete choice reaction tasks are the result of incorrect selections, but errors in force production can also arise from incorrect executions. ERPs were obtained while participants produced low or high isometric forces with their left or right hand. As expected, incorrect choices of hand elicited an Ne/ERN. Interestingly, Ne/ERNs were also present in the less discrete selection error of an incorrect choice of force, but only when erroneously a low instead of a high force was chosen. In both force ranges, no Ne/ERNs were found after errors in execution. These errors showed a large positivity in feedback ERPs and, similar to correct responses, a prolonged negativity in response ERPs. We propose that, compared to selection errors, the time uncertainty aspects of execution errors and the resulting changing response representations prohibit error detection by the internal monitoring system responsible for generating the Ne/ERN.

Descriptors: Event-related potential, Error-related negativity, Error negativity, Motor control, Action monitoring, Force production

We spend our days walking, talking, picking up items, or pushing buttons and only become aware of these actions when we happen to trip, slip, drop something, or fail in any other way. Apparently, we are constantly monitoring our actions, but only become painfully aware of the need to change our behavior when something goes wrong. Adopting a more cautious strategy can indeed be a wise approach to prevent embarrassing slips of the tongue or to stop the cash machine from eating our credit card when we type in the wrong personal code again. In these everyday tasks people often automatically rely on the presence of external feedback in their environment. However, external feedback is often degraded or even absent in these situations and yet people are generally able to accurately perform their actions. So, when external feedback is not available, people seem to rely on a more internal feedback system to monitor their actions.

The existence of such an internal monitoring system has been demonstrated in a number of studies using EEG measurements. A sharp negative deflection appears in the event-related brain potential (ERP) around 100 ms after an error has been made. This ERP component is called the error negativity (Ne; Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991) or error-related negativity (ERN; Gehring, Goss, Coles, Meyer, & Donchin, 1993). The Ne/ERN seems to reflect the output of an error detection system that tries to match a representation of the actual behavior with a representation of the desired behavior. When these representations are clearly distinct, the matching process can be easily completed. It turns out that the easier the matching process is, the larger the amplitude of the Ne/ERN will be (e.g., Bernstein, Scheffers, & Coles, 1995; Coles, Scheffers, & Holroyd, 1998). Because of the early onset latency of the component, it is believed that it is impossible for external monitoring (using peripheral sources) to already have taken place. Therefore the Ne/ERN is thought to reflect the output of an error-detection process that relies on an internal monitoring system alone. Several studies, using various localization techniques, have found the anterior cingulate cortex as the most likely source for generating the Ne/ERN (see, e.g., Dehaene, Posner, & Tucker, 1994; Dikman & Allen, 2000; Holroyd, Dien, & Coles, 1998). The Ne/ERN is present in visual and auditory domains (e.g., Falkenstein et al., 1991) and after erroneous reactions that are made by hand, foot, or eye movements (Holroyd et al., 1998; Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001; Van’t Ent & Apkarian, 1999). A component comparable to the response-locked Ne/ERN has also been reported in feedback-locked ERP averages where the feedback informs the participant that he or she has made an error (e.g., Holroyd & Coles, 2002; Luu, Flaisch, & Tucker, 2000; Mittner, Braun, & Coles, 1997). To date, the Ne/ERN has been studied mostly in tasks involving discrete choices like the Eriksen Flankers task (Eriksen...
types of tasks in everyday life consciously paying attention to external feedback plays an important role in error prevention, but it remains unknown how the internal monitoring system is involved in these actions and possible errors.

**Types of Errors in Motor Control Tasks**

Unlike errors in discrete choice tasks, movement errors are not exclusively errors in response selection. In motor tasks, a distinction has to be made between, on the one hand, errors in program (or response) selection and, on the other hand, errors in program (i.e., movement) execution. According to Schmidt (1976), these different errors are the result of two different processes, each having its specific movement goal. The environmentally defined goal of, for example, catching the ball in a game of volleyball, cannot be achieved when the performer’s incorrect choice of program is using an upper hand defense, when an underhand play is needed. The second process involves activating the relevant muscles to achieve the environmentally defined goal. When the performer has correctly selected an underhand defense strategy but he or she produces an incorrect force, it is possible that the ball will still land outside the boundaries of the field. Consequently, even when the program selected is correct, an error in program execution can still lead to a performance error.

Errors in program execution can be the direct result of unexpected events in the environment or of noise added to the deterministic movement signal. This so-called neuro-motor noise plays a central role in recent theories on speed–accuracy trade-offs in aiming tasks (De Jong & Van Galen, 1999; Slifkin & Newell, 1999; Van Galen & De Jong, 1995). The absolute amount of noise, and therefore the variable error in these tasks, is larger when movements are faster or when produced forces are higher. Generally, a distinction is made in motor control between fast preprogrammed movements and slower movements that consist of at least two components. A slow movement like grasping or pointing begins with a preprogrammed action, but in the second part of the slow movement available feedback is used to make adjustments. These adjustments can be necessary to control for the neuro-motor noise added to the preprogrammed signal or even to correct for an incorrect program selection. As Ne/ERNs are related to the moment of response onset, measuring them in motor control tasks corresponds therefore to measuring the monitoring process of the preprogrammed action alone. It is unknown whether errors in program execution are monitored in the same way as errors in choice of program. We are interested in whether and if so how the internal monitoring system detects these different types of errors. Or to be more precise, will differences in program selection and program execution errors be reflected in the amplitude or latency of the Ne/ERN?

To reduce movement artifacts as well as possible and to keep the design closely related to original Ne/ERN paradigms, we constructed a four-choice isometric-force production task. Participants had to choose between producing a high or a low target force with either their right or left index finger. When there are only two possible, nonoverlapping, discrete response categories, as is the case in choices of hand in a two-choice reaction task, the detection of the error is a fairly simple and fast process. It has been proven in a number of studies that these response selection errors lead to a clear Ne/ERN (see, e.g., Falkenstein et al., 1991; Falkenstein, Hohnsbein, & Hoormann, 1995; Gehring et al., 1993; Gehring, Coles, Meyer, & Donchin, 1995). In the present study, the experimental task consists of selecting a program (left or right index finger and high or low target force) and executing the program (producing the programmed amount of force). The program selection process of choosing a high or low target force is comparable to the choice of hand selection, as both processes are discrete response selections involving a stimulus–response mapping. However, the response categories underlying the stimulus–response mapping for the force selection processes vary on a continuous dimension. No intermediate categories exist between choosing a left or right hand, but there are numerous categories between choosing a high or low force. We therefore hypothesized that errors in choice of force level will lead to an Ne/ERN because the error itself, an incorrect stimulus–response mapping, is a discrete process. However, the amplitude of this Ne/ERN is expected to be smaller than the Ne/ERN following an incorrect choice of hand, because the response categories vary on a continuous dimension and will lead to a more difficult formation of representations, and therefore result in a more difficult matching process. A study by Luu, Flaisch, and Tucker (2000) using a reaction time deadline showed the presence of an Ne/ERN after trials that were responded to very late. The amplitude of this Ne/ERN was reduced compared to the amplitude of the Ne/ERN after incorrect choices of hand, thus supporting our current hypothesis that less discrete representations will lead to smaller Ne/ERN amplitudes.

Contrary to these more discrete program selections, program executions involve very different processes. Inaccurately exerted forces cannot be classified into discrete response categories. Besides, it is not certain whether representations of the responses are available to the system at the moment of response onset. It is evident that when these representations are unavailable, the matching process cannot be executed and, as a result, an Ne/ERN will not be generated. However, when representations of responses in program execution are available at the moment of response onset and if the Ne/ERN is indeed the reflection of a generic error detection mechanism, Ne/ERN activity is also expected in the context of errors in program execution.

**External versus Internal Feedback**

To minimize the use of feedback during the force production process, participants were asked to produce fast, preprogrammed actions, that is, short-lasting isometric-force productions. As a result, online control and available feedback during the response were reduced to a minimum. Instead, external feedback was visually given 2 s after stimulus onset. It must be noted that with this procedure, ERPs measured from feedback onset could be of use to examine the differences between errors in program selection and errors in program execution more closely. If there is indeed a difference between these two types of errors at the moment of response onset, it is interesting to see how these differences evolve over time. Presenting delayed visual feedback and measuring ERPs time-locked to this feedback provided us the means to investigate the effects of feedback information on the different types of errors.
Method

Participants
Eighteen undergraduate students (8 men) from the University of Nijmegen, ranging in the age from 18 to 25 years, participated in this experiment. They were all paid for their participation. All participants were right-handed and had normal or corrected-to-normal vision.

Design
We used a four-choice isometric-force production task. Depending on the shape (triangle/cross) and color (red/blue) of the stimulus, participants produced a short-lasting high or low force with their left or right index finger. Two seconds after stimulus onset, participants received visual feedback. Feedback consisted of a picture of a hand pointing to the left (correctly exerted force), pointing upwards (exerted force was too high) or pointing downwards (exerted force was too low). When participants made an incorrect choice of hand, the stimulus would also show an “X” in the palm of the hand. A low force was defined as 20% of the participants maximum voluntary contraction (MVC) and a high force as 40% MVC. Because higher forces lead to higher absolute standard deviation values (e.g., Van Galen and De Jong, 1995), the boundaries for correct responses were set according to a logarithmic scale ($\Delta \log(\text{Force}) > 0.15$). Consequently, correct feedback was presented when low force targets were responded to in the range from 14 to 28% MVC and high force targets in the range from 28 to 56% MVC.

Procedure
Participants were seated with their forearms resting on a flat desktop. The position of the hand and forearm was adjusted so that both fingertips of the index fingers rested on the load cell while participants kept their fingers stretched. After being familiarized with exerting forces using the push buttons, the MVCs for both the left and right index finger were assessed. Participants were asked to briefly press as hard as they could on the push button for seven consecutive times with one index finger. The maximum and minimum force values of these seven measurements were discarded. An average was computed of the remaining five values. This average became the MVC value, which was determined for both the left and right index fingers of each participant. After applying the electrodes for the EEG measurements, participants received written and verbal instructions. The instructions explained the procedure and stressed the importance of correct posture and the moment of eye blinks during the experiment (i.e., after the feedback stimulus had disappeared). The practice session that followed consisted of two parts. First, participants practiced their low and high force targets with their left and right index fingers separately. During this stage of practice they received delayed visual feedback about their force productions (i.e., curves showing the time course of the forces they produced), reaction times (RTs), and exerted peak force values. An RT deadline, indicating whether the response was given in time, was set at the relatively easy value of 1,200 ms during the practice block. In the second part of the practice session, stimuli were presented randomly to fully simulate the experimental conditions. The delayed visual feedback was now minimized to stimuli indicating whether the exerted force was correct, too high, or too low and whether the correct index finger was used. The experimental phase consisted of 10 blocks of 80 trials. RT deadlines, defining the criterion of presenting feedback indicating that the response was given too late, were, when necessary, adjusted between blocks to keep error performance comparable over blocks (10–15%). Participants first received a fixation point (1,000 ms) immediately followed by the stimulus (1,000 ms). After the stimulus, a blank screen (1,000 ms) preceded the visual feedback stimulus (1,000 ms) that ended the trial sequence. One experimental session lasted about 3 hr, including preparation and breaks.

Force Production Recording
Force data were collected using a load cell transducer (type BC302, DS Europa s.r.l., Italy). The output from the load cell was amplified with a low drift instrumentation amplifier (type INA125, Burr Brown, USA), using a gain factor of 500. The excitation supply of 5 V was delivered by the instrumentation amplifier and the amplifier was followed by a second-order 16 Hz low-pass filter before the signal. This output was sampled in epochs starting from stimulus onset and ending 1,500 ms later at 1000 Hz by a 16-bit analog-to-digital converter (Data Acquisition System PCI-6033E, National Instruments, USA) controlled by a Pentium 550 MHz computer. Special software was designed to allow online measurement of force production recording on a Windows controlled system. Calibration was achieved by using regression analysis to determine the function relating the force applied by use of weights of various magnitudes to that of the voltage output from each load cell. The moment of response onset was set at an absolute threshold value just above noise level, which, on average, corresponded to 1% MVC.

Psychophysiological Recording
The electroencephalogram (EEG) was recorded from 27 tin electrodes mounted in an elastic electrode cap (Electrocap international). Electrodes were placed at 7 midline (Fpz/AFz/Fz/FCz/Cz/Pz/Oz) and 20 lateral (FP1-2/F7-8/F3-4/FC5-6/T3-4/C3-4/CP5-6/T5-6/P3-4/O1-2) locations in accordance with the international 10-20 system. All electrodes were referenced to the left mastoid. The vertical electrooculogram (EOG) was recorded bipolarly from electrodes placed above and below the right eye. The horizontal EOG was also recorded bipolarly from electrodes lateral to both eyes. All electrode impedances were kept below 5 kΩ. EEG signals were recorded in epochs starting both 300 ms before stimulus and feedback onset and ending 1,800 ms later. The EEG and EOG signals were amplified using a time-constant of 8 s and a bandpass between 0.02 and 30 Hz. All signals were digitized with a sample rate of 200 Hz using a 16 bit A/D converter.

Results

Preparation of Data
Brain activity before movement or force production is reflected in the EEG, in so-called movement-related potentials (MRPs). Components of these MRPs are, for example, the Bereitschaftspotential or readiness potential, the premotion positivity, and the motor potential (see, e.g., Kornhuber & Deecke, 1965; Kristeva, Cheyne, Lang, Lindengen, & Deecke, 1990). Negative potentials are also present during the movement (movement monitoring potential, or MMP; Foit, Grozinger, & Kornhuber, 1982; Grünwald-Zuberbier & Grünwald, 1978) and seem to be

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1The notation of $\Delta \log(\text{Force})$ is used because the boundaries were set by both adding and subtracting 0.15 from the logarithmic values of the target forces 20 ($\log 20 = 1.30$) and 40 ($\log 40 = 1.60$).
enhanced by higher task complexity (Niemann, Winker, Hufschmidt, & Lucking, 1994), increasing force level, and especially higher rate of force development (Slobounov, Johnston, Chiang, & Ray, 2002; Slobounov, Ray, & Simon, 1998). These findings strongly suggest that this negative potential does not just reflect motor activity itself, but a monitoring process of these activities. Similar to the Ne/ERN, these potentials are most distinct at the FCz and Cz electrode positions placed directly above the motor cortex (MC). Measuring Ne/ERNs in motor control tasks will therefore lead to possible overlapping of the Ne/ERN and MMP components. To reduce this interference, we first analyzed the rate of force development (peak velocity) for correct high and correct low forces (see Figure 1) for all participants. This resulted in a significantly higher rate of force development for high forces compared to low forces, \( F(1,18) = 321.05, p < .001 \). This result combined with the literature concerning MMPs led us to conduct separate analyses for forces exerted in the low force range and forces exerted in the high force range.

For the analyses, all trials were assigned to the following response categories (see Table 1 for an overview): fully correct (defined as correct choice of hand and perfectly exerted force), correct (correct choice of hand and correctly exerted force), incorrect choice of hand (force is exerted with the incorrect index finger), incorrect choice of force (correct choice of hand but exerted force is incorrect and opposite from target force), and inaccurately exerted force (correct choice of hand but exerted force is incorrect and not opposite from target force). Next, these categories were classified according to target force level (high/low). This division was not possible for the incorrect choice of hand category because of an insufficient number of trials. Consequently, the total number of response categories amounted to nine. The number of errors in one or more of the nine defined categories was too small to obtain reliable ERPs for four participants. Moreover, two participants were removed because of excessive artifacts in the EEG signal. All further analyses are therefore based on the data of the remaining 12 participants.

Trials that showed activation from both index fingers or that were not responded to before the deadline were not included in the averages (6.5%). Also, trials exerted in the unclear area overlapping the two force levels (26 < > 32% MVC) were excluded from the averages (10.3%). The reason for this exclusion was that errors in exerted force in this area could not exclusively be assigned to a response category, because it would always remain unclear whether the error was the result of an incorrect selection or of an incorrect execution. ERPs for error and correct trials in this area did indeed not show any differences, \( F < 1 \).

### Data Analyses

Mean RTs, times to peak force, exerted forces, and amplitudes from each participant were entered into a repeated-measures General Linear Model (GLM). Unless otherwise stated, the analyses always involved planned comparisons from the means of the tested response category to the means of the corresponding fully correct category.

### Behavioral Data

Mean MVC values in newtons (N) were entered into a GLM with repeated measures on hand (left vs. right). The MVC for the right index finger of the right-handed participants was larger (37.30 N) than the MVC for the left index finger (32.73 N), \( F(1,11) = 5.47, p < .05 \). The remaining behavioral results and descriptive data are summarized in Table 2, in which plus signs indicate whether mean RT or mean time to peak force values in a certain category differed significantly from the accompanying fully correct category. The mean RTs and times to peak force for the two correct categories were entered into a GLM with repeated measures on category (fully correct vs. correct) and force target (low vs. high). Low forces were responded to slower (554 ms) compared to high forces (517 ms), \( F(1,11) = 27.20, p < .001 \). There was no difference between the two correct categories, \( F < 1 \), and also the interaction with force target was not significant, \( F(1,11) = 1.20, p = .30 \). The same analyses were conducted for time to peak force. High force responses lasted longer (190 ms) compared to low force responses (153 ms),

### Table 1. Exerted Force Criteria for Assigning Trials to Different Response Categories and the Number of Trials as a Percentage of the Total Number of 800 Trials plus Standard Deviations in Parentheses

<table>
<thead>
<tr>
<th>Response category</th>
<th>Low force target</th>
<th>High force target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Criteria (A log [Force] from target)</td>
<td>Range of exerted force (% MVC)</td>
<td>Number of trials (% of total)</td>
</tr>
<tr>
<td>Fully correct</td>
<td>(&lt; \pm 0.01)</td>
<td>19 &gt; 21</td>
</tr>
<tr>
<td>Correct</td>
<td>(\pm 0.01 &lt; \pm 0.15)</td>
<td>14 &lt; 19 and 21 &gt; 26</td>
</tr>
<tr>
<td>Incorrect choice of force</td>
<td>&gt; +0.2</td>
<td>32</td>
</tr>
<tr>
<td>Inaccurately exerted force</td>
<td>&lt; - 0.15</td>
<td>14</td>
</tr>
<tr>
<td>Incorrect choice of hand</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

### Figure 1. Force development in time for the fully correct high and low forces based on the force production data of all 18 participants. Single force productions were normalized according to 20 equally sized steps relative to force duration and plotted against the average force durations.
F(1,11) = 34.43, \( p < .001 \). Again, no difference was present between the two correct categories, \( F(1,11) = 1.51, p = .24 \), and the interaction was not significant, \( F(1,11) = 1.08, p = .32 \).

**Psychophysiological Data**

Because the recorded MMP activity was affected by force level and rate of force development, a different approach to the ERP analyses had to be taken compared to the behavioral analyses. For the ERP analyses, the high and low force ranges could not be categorized on the basis of the original target force as was the case for the behavioral analyses, but instead these analyses had to be related to the actually exerted force value. This only had consequences for the incorrect choice of force category. When an incorrect choice of force was made, a high force target resulted in a low exerted force. Therefore in the incorrect choice of force category, originally high force targets were compared to fully correct low force trials and originally low force targets were compared to fully correct high force trials.

EEG and EOG records were examined for artifacts and excessive EOG amplitude during an epoch from 100 ms preceding response onset to 300 ms after response onset and from 100 ms preceding feedback onset to 500 ms after feedback onset. Trials were not included in the averages when vertical or horizontal EOG signals were larger than 50 \( \mu V \), when manual scanning showed the presence of beginning or ending eye blinks in the selected epoch, and when EEG signals exceeded 75 \( \mu V \) (5.9% of total data set). ERPs were averaged time locked to response onset and feedback onset for each participant and each category. For the ERPs measured from response onset, Nc/ERN amplitude was defined as the most negative peak in the 0–200-ms window after response onset at electrode Cz, where Nc/ERN amplitude was found to be maximal. An Nc/ERN was present in a particular category when the Nc/ERN amplitudes of that

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**Table 2. Force and RT Results (Standard Deviations in Parentheses) for the Different Response Categories for the Low and High Force Targets**

<table>
<thead>
<tr>
<th>Response category</th>
<th>Low force target</th>
<th></th>
<th></th>
<th>High force target</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RT (ms)</td>
<td>Time to peak force (ms)</td>
<td>Peak force (% MVC)</td>
<td>RT (ms)</td>
<td>Time to peak force (ms)</td>
<td>Peak force (% MVC)</td>
</tr>
<tr>
<td>Fully correct</td>
<td>554 (105)</td>
<td>153 (48)</td>
<td>20.0 (0.6)</td>
<td>514 (93)</td>
<td>188 (62)</td>
<td>40.0 (1.2)</td>
</tr>
<tr>
<td>Correct</td>
<td>554 (109)</td>
<td>154 (45)</td>
<td>19.7 (3.4)</td>
<td>521 (90)</td>
<td>192 (62)</td>
<td>42.3 (6.4)</td>
</tr>
<tr>
<td>Incorrect choice of force</td>
<td>576 (103)*</td>
<td>139 (42)**</td>
<td>12.4 (1.3)</td>
<td>514 (108)</td>
<td>224 (83)**</td>
<td>60.4 (3.9)</td>
</tr>
<tr>
<td>Inaccurately exerted force</td>
<td>581 (143)</td>
<td>169 (56)*</td>
<td>23.9 (10.9)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Note:* \(*RT or time to peak force differs significantly \( p < .05 \) from the corresponding fully correct category; **\( p < .005 \); ***\( p < .001 \).
category differed significantly from the Ne/ERN amplitudes of the corresponding fully correct category. For the ERPs measured from feedback onset, the mean amplitudes of electrode Cz in the time window 250–500 ms after feedback onset for the different categories were analyzed.

**ERPs from Response Onset**

To check whether MMP activity was indeed reflected in ERPs measured from response onset, we first entered the mean amplitudes into a GLM with repeated measures on the two correct categories (fully correct vs. correct) and force range (high exerted force vs. low exerted force). Figure 2 shows the ERPs for the correct categories and force range (high amplitudes into a GLM with repeated measures on the two measured from response onset, we first entered the mean amplitudes of electrode Cz in the time window 250–500 ms after feedback onset for the different categories to the fully correct category alone. As explained in the preparation of data section, the incorrect choice of hand category could not be divided according to force level. The mean exerted force for this category was 23.9% MVC, which belongs to the low force range. Incorrect choices of hand are therefore compared to fully correct trials exerted in the low force range only (see Figure 3 and Figure 4).

**Low force range.** Incorrect choices of hand were followed by an Ne/ERN at Cz, $F(1,11) = 8.00, p < .02$, peaking around 110 ms. Incorrect choices of target force level showed an Ne/ERN, $F(1,11) = 9.46, p < .02$, peaking later around 135 ms, $F(1,11) = 22.00, p < .005$. Although Figure 3 suggests a difference in size, the amplitudes of the two Ne/ERNs did not differ significantly, $F(1,11) = 3.15, p = .10$, probably due to the relatively large standard deviations ($SD$) of both categories ($SD$ is 8.75 µV for incorrect choice of hand and 3.99 µV for the incorrect choice of force). ERPs for inaccurately exerted force trials did not show any error-related components differing from the ERPs for fully correct responses, $F(1,11) = 1.30, p = .28$.

Figure 5 depicts the topographical distributions over time for the four different categories in the low force range.

**High force range.** Incorrect choices of target force did not show an Ne/ERN, $F<1$, and ERPs for inaccurately exerted force trials did not show any error-related components differing from the ERPs for fully correct responses either, $F(1,11) = 2.59, p = .14$.

**ERPs from Feedback Onset**

*Low force range.* ERPs measured from feedback onset following fully correct trials were more positive than feedback trials following incorrect choices of hand, $F(1,11) = 4.95, p < .05$. For both feedback after incorrect choices of target force level, $F(1,11) = 5.12, p < .05$, and feedback after inaccurately exerted force trials, $F(1,11) = 6.33, p < .05$, the ERPs showed a large P300. The amplitudes of these P300s did not differ significantly, $F<1$.

*High force range.* For both feedback after incorrect choices of target force level, $F(1,11) = 24.78, p < .001$, and feedback after inaccurately exerted force trials, $F(1,11) = 9.66, p < .02$, the ERPs showed a large P300. The amplitudes of these P300s did not differ significantly, $F(1,11) = 1.22, p = .29$.

**Discussion**

Participants performed a four-choice reaction task in which they had to choose between executing a short-lasting high or low force with either their left or right index finger. We replicated the presence of an Ne/ERN after incorrect choices of hand as found previously on non-force production tasks using push buttons. We also found a comparable Ne/ERN after incorrect choices of force, but only when participants chose a low instead of a high force, so when the actually exerted force belonged to the low force range. No Ne/ERNs were found after inaccurately exerted forces measured from response onset in both force ranges, but the feedback-locked ERP averages showed significant positive deflections for these categories.

**The Presence of a Negativity in All Categories**

A notable result is the presence of a negativity after response onset in all categories. One explanation comes from literature concerning motor potentials and, to be more precise, movement
monitoring potentials (MMPs, see the Introduction). Slobonouv et al. (1998, 2002) found that these MMPs were especially larger (i.e., more negative) after forces with a higher rate of force development. Our findings that there was a significant higher rate of force development for high forces compared to low forces and that correct high forces were more negative in the critical Ne/ERN time window are therefore indications that MMPs are probably responsible for the negativity found in all categories. As a result, it was necessary to conduct separate analyses for the high and the low force range. However, other possible interpretations should not be overlooked.

Another explanation for the found negativity comes from Ne/ERN literature where sometimes Ne/ERNs are reported after correct trials (see, e.g., Coles, Scheffers, & Holroyd, 2001; Falkenstein, Hoormann, Christ, & Hohnsbein, 2000; Scheffers & Coles, 2000; Vidal, Hasbroucq, Grapperon, & Bonnet, 2000). Scheffers and Coles showed that this correct response negativity, or CRN, could result from uncertainty about the given response. This uncertainty could have had some effect on the ERP, because the force is actually still being produced in (the beginning of) the critical Ne/ERN time window. It is reasonable to assume that while a participant is producing a force, uncertainty about this production process arises and persists. The production process is, in fact, ended at the moment of peak force when the participant releases the button. This time to peak force was longer (188 ms) for high forces than for low forces (153 ms), $F = 32.21, p < .001$, and therefore the uncertainty could last longer for higher forces. However, more difficult processes would also lead to more uncertainty. Ten (out of 12) participants indicated in a questionnaire that they had more difficulty executing low forces.
than executing high forces (see also the percentage overview in Table 1). Uncertainty caused by difficulty could therefore not influence our negativity, because the ERPs showed the reverse, that is, a higher negativity after high force productions. Therefore, it remains unclear whether the found rising negativity is really caused by uncertainty about the ongoing force production process. It is, however, very well possible that the negativity is a combination of both MMP activity and uncertainty of the force production process.

The presence of an Ne/ERN after incorrect choices of hand was an indication that although MMPs were present and interfered with Ne/ERN signals, Ne/ERNs were still recognizable because they were superimposed on this MMP signal. Although analyses for incorrect choices of hand were limited to the low force range because of the mean exerted force in this particular category, it is important to note that the Ne/ERN after incorrect choices of hand was of such a magnitude that it was also higher than the high force MMP signal, $F(1,11) = 5.18$, $p < .05$. As predicted, an Ne/ERN was present after incorrect choices of force in the low force range, but this result was not found in the high force range. So both types of errors in response selection elicited Ne/ERNs in the low force range, but they were not both present in the high force range. Moreover, although inaccurately exerted forces do show a more negative ERP signal, no Ne/ERN was present after errors in program execution for both the low and high force range.

This latter result is probably induced by time uncertainty of this type of response, likely leading to latency jitter in the ERPs. An error of this type, whether due to neuro-motor noise or not, can be made at a moment in time that differs from response onset and consequently takes place after the preprogrammed action has been executed. In this case, the error is unknown to the system at the moment of response onset and can therefore not be seen in ERPs time locked to response onset. In addition, the representation of the force production process itself is constantly changing over time and therefore no easy comparison with the desired response can be made. These ideas were also confirmed by a pilot study in which we had participants perform the same task without receiving any feedback during the experiment. It turned out to be impossible for the participants to keep on performing the force production task correctly. During the experiment, they gradually deviated more and more from the target forces and consequently ended up with a very poor representation of the desired and actual responses. This pilot study showed that participants severely depend on the external feedback, given after the response is executed, to maintain their performance. Although we minimized the effects of latency jitter by demanding short-lasting force productions, time uncertainty aspects were apparently still present and made it impossible for the internal monitoring process alone to successfully monitor inaccurately exerted forces. As a result, an Ne/ERN is not generated after errors in program execution in this particular force production task.

An Ne/ERN is often followed by a positivity, the so-called error positivity or Pe (Falkenstein et al., 1991, 1995), likely reflecting the conscious error detection process (Falkenstein et al., 1991, 2000; Nieuwenhuis et al., 2001). Figure 3 suggests that this Pe is indeed present in the two categories in the low force range where an Ne/ERN is found, and, because of the possibility that this Pe could also interfere with the MMP signal, we depicted in Figure 5 the topographical distributions in time for the different categories in the low force range. These distributions show how activity over FCz and Cz increases locally, immediately after response onset in all categories, typical for both Ne/ERN and MMP activity and subsequently decreases very rapidly after 150 ms. However, the latter is only the case for the two categories in which an Ne/ERN is also present and is therefore considered to be a reflection of the following Pe. In the categories where no Ne/ERN is found, a similar rising, but less intense negativity starting after response onset over these central midline electrodes is present. But, instead of a rapid decrease after 150 ms, this negativity, which seems to spread out to more posterior sites as well, persists during the response and even continues after the response is ended. Therefore, Figure 5 may suggest that activity over these areas is prolonged in categories where an Ne/ERN is absent, compared to the categories in which an Ne/ERN is present. We should note that the activity of the Pe perhaps cancels out the present sustained negativity, but, with regard to its functionality of conscious error processing, it is more plausible to assume that the sustained negativity is no longer present after an Ne/ERN followed by a Pe. Furthermore, these effects do not just reflect motor activity itself, as they are unrelated to peak force or force duration. The inaccurately exerted force category, for example, has the lowest peak force and the shortest force duration, but does show the prolonged activity carrying on until at least 250 ms after response onset. Irrespective of the origin of this activity (Ne/ERN or MMP), this could be an indication that monitoring processes continue until an error is detected, thus supporting the hypothesis that a motor control task leads to prolonged action monitoring compared to a discrete choice task. The need for this prolonged monitoring only exists when no error is detected by the internal monitoring system responsible for generating the Ne/ERN and is therefore present in both the inaccurately exerted force and fully correct categories.

**High Force Range Results versus Low Force Range Results**

When looking at the low force range results alone, our results are in accordance with our predictions. Although not significantly different in amplitude, both types of errors in program selection elicited Ne/ERNs. The finding that the Ne/ERN peaks earlier in time after an incorrect choice of hand compared to the Ne/ERN after an incorrect choice of force could be interpreted as a reflection of the order of processing stimulus information (for a discussion see Bernstein et al., 1995). Participants indicated that the strategy they used involved first selecting the index finger followed by the selection of target force.

The result that in the high force range no Ne/ERN is present after an incorrect choice of force is rather unexpected and hard to interpret from solely an error monitoring point of view. The literature on speed–accuracy trade-off gives us some information on functional differences between high and low force productions. From these speed–accuracy trade-off studies it is known that exerting higher forces will lead to higher absolute standard deviations from the target (see, e.g., Van Galen & De Jong, 1995). It is conceivable that these absolute differences between high and low forces have their influence on forming a representation about the actual response. Moreover, from long-lasting force production studies it is known that information transfer related to targeted force production is optimized (i.e., an optimal signal-to-noise ratio) between 25 and 35% MVC (see, e.g., Sliškin and Newell, 1999). When forces beyond this optimum have to be produced, a change in force generation mechanisms takes place. Until the optimum, increasing the
number of active motor units will lead to increased force. The optimum coincides with recruiting all available motor units and from that moment on, an increase in force production depends on modulation of discharge frequency (Kamen, Sison, Du, & Paten, 1995). It seems plausible to assume that these well-known phenomena studied extensively in speed–accuracy trade-off research also affect our error monitoring data. Although hypothetical, we would like to suggest that the higher standard deviations and, consequently, poorer signal-to-noise ratios in combination with different force production mechanisms may be responsible for causing a more difficult process of error monitoring in the high force range compared to the low force range. Future studies dedicated to this subject could provide us with more information on how these different processes exactly interact and how they affect the process of error monitoring.

Feedback-Locked ERP Results
The feedback-locked ERPs show a difference between the ERPs for feedback after a fully correct reaction and for feedback signaling an incorrect choice of hand. In a number of studies, a comparable negativity has been defined as the “feedback ERN” (e.g., Holroyd & Coles, 2002; Miltner et al., 1997). The Feedback ERN is thought to be elicited when negative feedback is presented when a participant did not expect it. Or, in other words, when the outcome is worse than expected and a mismatch between expected and actual feedback occurs. According to Holroyd and Coles, the feedback ERN is very much affected by reinforcement learning. When participants are learning a stimulus–response mapping, the feedback ERN is larger and reduces while gradually the mapping is learned. However, the response-locked Ne/ERN does the opposite: It is small or even absent in the beginning of the learning process and gets larger when the stimulus-response mapping is acquired. This theory would therefore not predict a feedback ERP after feedback signaling incorrect choices of hand in our study. Participants are very well aware of these errors and therefore the feedback only confirms what they already knew: They made an error. Learning the stimulus–response mapping was also not the issue in our experiment. Participants learned this mapping during the practice trials. But learning does play a huge role in the force production process. Force production performance improved during the experiment and participants used the feedback to keep up their force production performance. The latter was concluded from the pilot study mentioned earlier, in which participants deviated more and more from the target forces when no feedback was given. The reinforcement learning theory would therefore predict a feedback ERP after feedback signaling a force production error. However, no feedback Ne/ERNs were present in the feedback ERPs after force production errors. On the contrary, we found large P300s compared to feedback after fully correct trials. We are also convinced of thevalidness of our current results, as we found similar ERPs measured from feedback onset in a Flankers task without any force production requirements (de Brujin & Hulstijn, 2003).

As a result, we believe that our feedback-locked data do not show this feedback ERN component, but are a reflection of expectancy of the feedback stimulus. This expectancy is inversely reflected in the amplitude of the P300: The larger the expectancy, the larger the amplitude (e.g., Johnson and Donchin, 1980). Our data fit these P300 characteristics perfectly. Participants are always aware of incorrect choices of hand, and therefore the feedback stimulus has the highest expectancy and the smallest P300 amplitude. Correct feedback has a lower expectancy than feedback indicating an incorrect choice of hand because of the inherent uncertainty of the force production process. As a consequence, the P300 is larger compared to feedback signaling that an incorrect choice of hand had been made. The largest P300s are found after feedback signaling that an error in force production has been made. Along with the smaller expectancy of these feedback stimuli, caused by the uncertainty of the force production process, this type of feedback is also more important for participants. Our pilot study already showed us that participants needed to fully interpret and process the feedback information on force production in order to keep on performing the task at hand. This larger significance of the stimulus and the deeper information processing is also known to enlarge the amplitude of the P300 (Johnson, 1986, 1988). Taken together, we are convinced that our feedback-locked ERPs only show modulations of P300 activity and not of any feedback ERN-related components. From this point of view, the result that the P300 amplitude is smaller for the fully correct category in the high force range (5.21 μV) than the fully correct category in the low force range (7.65 μV), F(1,11) = 16.83, p <.005 (see Figure 4) can be interpreted as a reflection of the participants indicating they were having more difficulty exerting lower forces than higher forces.

Our experiment was novel in combining Ne/ERN research with a typical motor control task like force production. We have shown that despite the interference of MMP activity, it is still possible to look more closely at error monitoring processes of motor control tasks using ERP measurements and that this can lead to interesting new insights. Overall, our results show that response selection errors in force production can also elicit an Ne/ERN and that response execution errors do not. New experiments could give us important information on the relationship between the sustained negativity and the presumably prolonged action monitoring and whether, for example, extensive practice of a particular motor control task could lead to successful error detection by the internal monitoring system or whether the absence of the Ne/ERN is indeed a general phenomenon applicable to all types of errors in response execution.

REFERENCES


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