On-line executive control: An electromyographic study

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In a choice reaction time (RT) task, electromyographic (EMG) recordings allowed us to fractionate RT into two subcomponents, namely premotor time and motor time. This has been done for correct trials and errors. The analysis of the EMG burst and motor time (between EMG onset and overt response) showed that the EMG burst amplitude was reduced and the motor time was longer for errors than for correct responses. In the same way as posterror slowing on the RT was interpreted as revealing between-trials changes in executive control, the present data provide direct evidence for an on-line, within-trial, executive control.

Descriptors: Executive control, Motor time, Error, Electromyogram

It is well known that after an error, subjects are slower (RTs are longer; Rabbitt, 1966) and more accurate (error rate is lower; Laming, 1979) than after a correct response. These results demonstrate changes in speed–accuracy strategy: After an error, subjects are more cautious and take more time for responding. Such changes have often been attributed to between-trials executive control adjustments. Although such between-trials adjustments undoubtedly exist, recent data suggest that on-line, within-trial changes in executive control can also take place.

After the pioneering work of Coles, Gratton, Bashore, Ericksen, and Donchin (1985), who studied the particular trials in which an electromyographic (EMG) activation of muscles involved in the incorrect response preceded the execution of the correct response, Burle, Possamaï, Vidal, Bonnet, and Hasbroucq (2002) focused on these subthreshold EMG activations. The authors interpreted them as partial errors that were detected, aborted before reaching the overt response threshold, and successfully corrected. This interpretation implies an on-line, within-trial, executive control that allows the nervous system to detect, stop, and correct such partial errors.

If incorrect EMG activations are partial errors corrected in time, signs of such an on-line executive control should also be detectable on overt errors, even if it fails to stop the incorrect response in time. As a matter of fact, in typing tasks, Rabbitt (1978) showed, although indirectly, that response force is more often reduced on errors than on correct responses. Such a result suggests that erroneous response execution is inhibited on-line as proposed by Gehring and Knight (2000). Our aim was to further explore this possibility.

From a chronometric point of view, if response execution receives an inhibition, the duration of the execution processes should increase. To estimate the duration of response execution processes, one can record the EMG activity of response agonists. Indeed, EMG recording allows one to split the RT into two components: the premotor time (PMT), from the response signal to EMG onset, and the motor time (MT), from EMG onset to mechanical response. If any portion of RT interval reflects solely the duration of motor processes, surely it is the MT.

If erroneous response execution is inhibited on-line, the MT should be longer for errors than for correct responses, even though error RT is usually shorter than correct RT (Rabbitt, 1966). However, one could argue that a lengthening of the MT simply corresponds to a different cortico-spinal command. According to models of EMG (Meijers, Teulings, & Eijkman, 1976), the leading edge of the EMG activity can be related to the variance of the motor units onset time: The lower the variance, that is, the more synchronized the motor units discharge, the steeper the EMG activity. Hence, differences of the leading edge in the EMG activity reflect differences in the nature of the motor command (Hasbroucq, Mouret, Seal, & Akamatsu, 1995; Possamaï, Burle, Osman, & Hasbroucq, 2002).

Therefore, if motor commands are qualitatively different on error trials due to some upstream processes rather than due to an attempt to inhibit on-line, one should predict no difference in the leading edge of the EMG burst between errors and pure-correct trials. Conversely, if errors are inhibited on-line after the initial command has been sent, the leading edge of EMG bursts should be identical on errors and on correct responses, but afterwards,
the EMG activity should be reduced for errors compared to correct responses. This effect would correspond to the occurrence of the inhibition process (McGarry & Franks, 1997).

We tested these two hypotheses by reanalyzing the data of a previously reported experiment (Carbonnell, Hasbroucq, Grapperon, Bonnet, & Vidal, 2002): All the errors and all the correct responses have been taken into account, whatever the nature (correct or incorrect) of the preceding trial (i.e., the analyses are not based on sequential effects).

Materials and Method

Participants

Twelve participants (one woman), aged 20–50 years (mean 31), volunteered for the experiment. All were right-handed with normal or corrected-to-normal vision.

Design and Stimuli

Participants had to respond as fast and accurately as possible by pressing the left or the right button of a response pad (NeuroScan), with their left or right thumb, respectively, depending on the nature of a response signal. The response signals were the French words droite (right) or gauche (left) (Stim system of NeuroScan). The stimulus–response mapping was incompatible: Participants were asked to respond with the right thumb when the response signal was gauche and with the left thumb when the response signal was droite (this incompatible condition is known to provide a larger error rate).

The response signal was preceded by a preparatory signal that could provide (precue condition) or not (no precue condition) advance information about the forthcoming response. In half of the trials, the preparatory signal was the word droite or gauche, precuing which thumb to be used. In the other half, the preparatory signal was the French word neutre (neutral) and did not precue the thumb to be used. All the conditions were mixed. The stimuli were presented according to a pseudorandom sequence. The preparatory signal and the response signal were presented in the same way, and, in the precue condition, the preparatory signal was always identical to the response signal. In 9% of the trials, the response signal was the French word pièges (traps); participants were asked not to respond. This weak rate was included to encourage the participants to identify, and not simply detect, the response signal in the precue condition.

The preparatory signal was displayed for 1 s. The response signal appeared 1 s after the preparatory signal offset. The response signal was displayed until the response, or during 800 ms if participants failed to respond within this interval. Then, 500 ms after the response signal extinction, the next preparatory signal was presented.

Before the experimental session, participants performed a training block (110 trials). The experimental session comprised six blocks of 110 trials. After each block, participants had a few minutes of rest. Within each block, the precue and the no precue conditions were randomly mixed.

In the precue condition, the error rate was not sufficient (1%) for reliable analysis. Therefore, the data from the precue condition were discarded. In the following, only the data from the no precue condition have been taken into account.

Electrophysiological Recordings

The EMG was recorded from the flexoare pollicis brevis of each thumb, by paired surface Ag/AgCl electrodes (6 mm in diameter), amplified (5,000 times), filtered (10 Hz–1 kHz), full-wave rectified and integrated (integration window: 5 ms), and then digitized (sampling rate: 256 Hz).

Although automated algorithms have proved to be useful, the EMG onset was detected by visual inspection of each trial (Hasbroucq, Possamaï, Bonnet, & Vidal, 1999; Van Boxtel, Geraats, Van den Berg-Lessen, & Brunia, 1993): The trace corresponding to the EMG activity was displayed on the computer screen and the EMG activity onset was marked by means of the computer mouse. At this stage, the experimenter was unaware of the nature (correct or incorrect) of the trial he was looking at.

Classification of Trials

Correct trials were categorized according to whether or not the activation of the agonist involved in the required response was preceded by an activation of the agonist involved in the alternative response. Trials presenting such a dual activation were termed “incorrect EMG” and the other trials were termed “pure-correct.” For that reason, trials were sorted into three categories, labeled pure-correct, incorrect EMG, and error.

However, the number of incorrect EMG trials being too low for reliable estimation of the various chronometric variables, they were not analyzed (see below).

Data Analysis

The chronometric indices analyzed in the present study were premotor time (from response signal to EMG onset) and motor time (from EMG onset to button press).

In addition to the usual analyses of the mean values, distribution analyses were performed. To this aim, the “Vincent averaging” technique was used (Ratcliff, 1979; Vincent, 1912). Basically, the PMT and MT distributions were binned in classes of equal size (same number of trials), and the mean of each bin was computed. This was done for each participant separately and the mean values of each bin were then averaged across participants.

Results

During this study, the electroencephalographic (EEG) activity was recorded for other purposes (Carbonnell et al., 2002): The authors have shown that the electrical activity recorded over the supplementary motor area was higher in the precue than in the no precue condition, whereas the electrical activity recorded over the primary sensory motor area was insensitive to the precue. Because of EEG artifacts, tonic EMG activities, and omissions, 9% of the trials were rejected. The remaining trials were distributed as follows: 92% pure-correct, 5.5% error, and 2.5% incorrect EMG (not analyzed).

Chronometric indices and EMG activities were compared across correctness by using the two-tailed, two-paired Student’s t test.

Chronometric Variables

Mean PMT was shorter for erroneous trials (443 ms) than for pure-correct trials (476 ms), t(11) = 2.23, p < .05. In contrast, mean MT was longer for erroneous trials (79 ms) than for pure-correct trials (72 ms), t(11) = 2.67, p < .05.
Figure 1. Cumulative density functions of premotor time (PMT, top) and motor time (MT, bottom), for pure-correct and erroneous trials.

**Distribution Analyses**

Only 9 participants had sufficient erroneous trials (at least 10 errors) for a distribution analysis to be performed and were therefore included. These participants had a pattern of results very similar to the entire group, and the results reported above also hold for this sub-group (PMT: $t(8) = 2.51$, $p < .05$; MT: $t(8) = 2.33$, $p < .05$). Because of the small number of erroneous trials, only five bins were used in the Vincent averaging.

Figure 1 presents the cumulative density functions for the PMT (bottom) and the MT (top), and for pure-correct and erroneous trials.

For PMT and MT, pure-correct and error distributions are regularly ordered without crossing. To confirm these findings, an ANOVA was performed with correctness (pure-correct vs. error) and quantile (five bins) as within-subject variables.

On PMT, the ANOVA reveals an effect of correctness, $F(1,8) = 6.291$, $p < .05$, an effect of quantile, $F(4,32) = 202.9$, $p < .0001$, which is trivial, but no interaction between these two factors, $F(4,32) < 1$. On MT, the ANOVA reveals an effect of correctness, $F(1,8) = 5.324$, $p < .05$, an effect of quantile, $F(4,32) = 219.6$, $p < .0001$, but no interaction between these two factors, $F(4,32) < 1$.

**EMG Activities**

Figure 2 presents electromyographic activities for errors and for pure-correct responses, time-locked to the EMG onset. The EMG activity seems smaller for erroneous trials than for pure-correct, although the leading edge of the two EMG activities seems perfectly superimposed during the first 30 ms after EMG onset. To confirm this observation, the surface under the curve was calculated for the 12 participants, in two time windows. The first time window corresponding to the leading edge ranged from 0 to 30 ms. There was no statistical difference between the erroneous and correct initial EMG bursts during this time window, $t(11) = .015$. The second time window encompassing the peak of the bursts ranged from 30 to 100 ms. This time window was chosen because at 100 ms the EMG bursts were still in their decrease phase in all the participants. Beyond this moment, there was a high between-subject variability in the ending of EMG bursts. The EMG activities during this time window were statistically different, $t(11) = 2.84, p < .02$.

**Discussion**

Although the PMT was shorter for errors than for pure-correct trials, the MT was longer for errors. Although the absolute value of this effect was small (7 ms), it was of the same magnitude as the shortening of the PMT ($-7\%$ vs. $+9.7\%$ for the PMT and the MT, respectively), and statistically significant because stable across subjects. Moreover, the distribution analysis showed that this effect was present on the whole distribution, invalidating the possibility that a particular class of trials led to an artefactual increase in mean MT. One could argue that the cause of MT lengthening was due to a problem that slows down the information processing as a whole. However, the PMT of errors should also be lengthened, which was not the case.

Another possible explanation of the MT lengthening on errors could be that erroneous responses are triggered by a cortico-spinal command that differs from that corresponding to correct responses. However, if that were the case, one should obtained correlative changes in the leading edge of the EMG bursts (Hasbroucq et al., 1995; Possamaï et al., 2002), which was not the case. Therefore, the reduction of EMG activity on errors is better explained by an additional inhibition occurring during the erroneous execution, in an attempt to stop it (McGarry & Franks, 1997).

In line with current theories of executive control, the above results can be interpreted as follows: During a trial, an executive control supervises the execution of the response. If the incorrect response is activated, the control system detects it, and an active process attempts to inhibit this incorrect activation. If this process succeeds, the incorrect activation is actively stopped, and an incorrect partial EMG response occurs; in that case, the
incorrect EMGs correspond to partial errors corrected in time, as proposed by Burle et al. (2002). If this process fails to inhibit the incorrect activation, an overt erroneous response is emitted: The only index of this mechanism at the peripheral level is the reduction of EMG burst. Because EMG activity and response force are related monotonically (Bigland-Ritchie, 1981), a weaker EMG activity results in a weaker response force, thereby slowing down erroneous response execution (longer MT). Whatever the outcome, overt or partial error, executive control adjustments occur (Burle et al., 2002; Laming, 1979; Rabbitt, 1966).

In the same way as the posterror slowing reported by Rabbitt (1966) has been interpreted as between-trials executive control, we interpret the reduction of errors EMG burst and the increase of errors MT as secondary manifestations of an on-line executive control (occurring within trial).

The last comment concerns the notion of point of no return, extensively debated in the literature (see Band & Van Boxtel, 1999, for a recent discussion). If we define the point of no return as the point in time after which any attempt to stop a response is no longer possible (Osman, Kornblum, & Meyer, 1986), then the present data provide arguments against such a notion. In contrast, if we define the point of no return as the point after which some attempts to stop a response are still possible but will inevitably fail, then the present data are compatible with such a notion. Therefore, it seems that a corrective attempt can be implemented until the very last phase of response execution, even though, after a given point, such attempts might become unavoidably inefficient.

REFERENCES


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