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On-line action monitoring of response execution: An electrophysiological study

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ABSTRACT

In between-hand choice-RT-tasks, small incorrect EMG activations occurring before the correct response ("partial errors") are assumed to reflect the detection, inhibition and correction of erroneous hand selection, revealing the existence of an action monitoring system, acting "on-line".

Now, EMG activations of the *correctly* selected hand muscles, too small to reach the response threshold, may also occur before these hand muscles produce an overt correct response ("partial corrects"). We hypothesized that partial corrects reflect incorrect execution of correctly selected responses. We found 1) that response force was smaller on trials preceding a partial correct trial and 2) that the Error Negativity, a performance sensitive ERP, assumed to reveal "on-line" action monitoring, was larger for partial corrects than for correct trials.

This also suggests that the competence of the action monitoring system is not restricted to selection errors but also extends to execution errors.

1. Introduction

It is often assumed that performance is controlled by a supervisory system that monitors ongoing actions (*e.g.* Botvinick, Braver, Carter, Barch, & Cohen, 2001; Rabbitt, 1966). For example, in reaction time tasks (RT), post-error increase of RT ("post-error slowing") suggests that, after an error, subjects become more cautious, in order to avoid committing new errors (Allain, Burle, Hasbroucq, & Vidal, 2009; Danielmeier & Ullsperger, 2011; Laming, 1979; Rabbitt, 1966; Ruitenberg, Abrahamse, de Kleine, & Verwey, 2014). This type of strategic adjustments would be triggered by the supervisory (also called action monitoring) system. Moreover, in between-hand choice RT tasks, a significant proportion of correct responses are preceded, in the same trial, by small incorrect EMG activations (of the "wrong" response), too small to reach the response threshold (Coles, Gratton, Bashore, Eriksen, & Donchin, 1985; Eriksen, Coles, Morris, & O'Hara, 1985; Smid, Mulder, & Mulder, 1990). The existence of these so called "partial errors" (Scheffers, Coles, Bernstein, Gehring, & Donchin, 1996) suggests that an action monitoring system can "on-line" detect, inhibit and correct inappropriate response activations before they result in overt errors (Allain et al., 2009; Burle, Possamaï, Vidal, & Bonnet, 2002). Finally, shortly after EMG onset and before the mechanical response, medial frontal areas generate large ERPs on errors (named "Error Negativity" or Ne: Falkenstein, Hohnsbein, Hoormann & Blanke, 1991 also called Error-Related Negativity or ERN: Gehring, Goss, Coles, Meyer, & Donchin, 1993), smaller ones on partial errors (Scheffers et al., 1996; Vidal, Hasbroucq, Grapperon, & Bonnet, 2000) and even smaller but still present ones on correct responses (Vidal et al., 2000). This early Ne sensitivity to performance indicates that a supervisory system "on-line" monitors ongoing actions. Recent intracerebral recordings (Bonini et al., 2014) showed that, whatever the nature of the response (correct, partial error, error), the Ne is mainly elicited by the SMA proper, indicating that this structure plays a leading role in action monitoring. When a choice between two (or more) effectors is required, errors likely correspond to the selection of the inappropriate effector. Although a large part of the literature on action monitoring deals with these selection errors, errors can also be due to the inappropriate execution of a correctly selected response.

Anguera, Seidler, and Gehring (2009) reported a sensitivity of the Ne to the magnitude of the error in reaching a correctly selected target. Such a sensitivity would indicate that the (in)accuracy in response execution is monitored by the supervisory system. However, according to the authors, the observed waveforms did not "resemble those of the ERN observed in more typical speeded button-press tasks" (p. 1877)

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with different time courses and latencies, and it is hard, therefore to firmly conclude that this ERP corresponds to an Ne. As a consequence, these results do not firmly establish that action monitoring extends to response execution.

Vocat, Pourtois, and Vuilleumier (2011) and MacLean, Hassall, Ishigami, Krigolson, and Eskes (2015) tackled the same question using prismatic adaptation to induce errors in a pointing task. On difference waves, they observed an error-related component, peaking about 70 ms after target reaching, which amplitude varied with error size. However, this procedure potentially confounded two factors: errors and adaptive error-reduction processes (Torrecillos, Albouy, Brochier, & Malfait, 2014). Moreover, "…the negative amplitude measured on "miss" trials is likely not evoked specifically by the event of touching the screen but rather the evoking stimulus is view of the limb prior to screen-touch." (MacLean et al., 2015, p. 335). According to this interpretation, this error-sensitive ERP is more readily identified with Feedback-Related Negativities (Miltner, Braun, & Coles, 1997) than with Ne. Inspection of waves time courses before subtraction on figure 3 of MacLean et al. (2015) also confirmed this view. According to this view, these data sets and those of Torrecillos et al. (2014) do indicate that the supervisory system is sensitive to execution errors but do not demonstrate that it can evaluate them "on-line" because these ERPs were externally triggered and too late to represent "on-line" action monitoring processes.

In a four-choice isometric-force production RT task, de Bruijn, Hulstijn, Meulenbroek, and van Galen (2003) asked subjects to produce, a weak or a strong brief keypress with their right or left index finger. Both selection (the produced force being opposite to the target force) or execution errors (inappropriate execution of correctly selected force) errors could occur. A "true" typical Ne was evoked by force selection errors for the weak force only, but the Ne was insensitive to force execution errors. However, according to the authors, the fact that force was constantly changing over time, probably hampered the comparison process of the executed force with a well-consolidated representation of the required force.

Armbrecht, Gibbons, and Stahl (2012), used a priming paradigm (Rosenbaum & Kornblum, 1982). A prime indicated in advance which of two possible response forces should likely be produced. In 25% of the cases, the RS did not confirm the prime. The authors reasoned that on invalid condition errors were mostly due to inappropriate choices of force. On the contrary, on valid condition, errors would necessarily be due to execution errors. The Ne was neither sensitive to errors of choice nor to errors of execution. They concluded that the force parameter was not monitored "on-line". Now, as discussed by Armbrecht et al.'s themselves, their data could allow another interpretation. Meckler et al. (2011) compared the effect of a response bias (80% *vs* 20%) on the amplitude of the Ne in a between-hand two choice RT task. In the unexpected condition (20%) the Ne was so large on correct trials and reduced on errors that no difference showed up between errors and correct responses, thus mimicking with the hand the data obtained by Armbrecht et al. (2012) with the force parameter. As discussed by Armbrecht et al. (2012) these data could easily account for the absence of modulation of the Ne on force selection errors, without resorting to the idea that the supervisory system is incompetent regarding force selection processes. This interpretation would reconcile Armbrecht et al.'s results and Bruijn et al. data. Now, on valid trials, Armbrecht et al. did not evidence any effect of (in)accuracy in responses execution and concluded that the action monitoring system was probably blind to execution errors. However, "Perhaps the participants were not able to establish an appropriate representation of the correct response, and thus a large uncertainty over response accuracy existed" (Armbrecht et al., 2012, p. 69); if this were the case, the supervisory system could not reliably sort accurate and inaccurate responses, and response correctness (accuracy) had no effect on the amplitude of the Ne.

In the present study we concentrated on force execution errors. In between-hand choice RT tasks some correct responses are preceded by subthreshold EMG activity in the muscles involved in the incorrect response (Burle, Allain, Vidal, & Hasbroucq, 2005; Masaki, Murphy, Desjardins, & Segalowitz, 2012; Vidal et al., 2000). These are considered as "partial errors" (*e.g.* Scheffers et al., 1996). Now, before the correct response, subthreshold activations may also occur in the muscles involved on the *correct* side. These are fewer than partial errors but occur in a non negligible proportion of correct responses. Since the force to be exerted on the response key does not vary, it is possible that these "partial correct" activities on the correct hand response, correspond to responses where the required force has not been correctly produced. In other word, these activities might correspond to execution errors regarding the force required to reach the overt response threshold. Therefore, we examined in the present study the sensitivity of the Ne to the presence of these partially correct EMG activities. To improve the spatial and temporal resolution (Burle et al., 2015) of EEG recordings, and compare our results with those of Armbrecht et al., we Laplacian-transformed our surface potential data. Finally, since participants' performance severely depend on post-response external feedback, (*e.g.* Ambrecht et al., 2012; de Bruijn et al., 2003), an auditory feed-back was delivered on each trial at the moment when the required force threshold was attained.

2. Materials and method

2.1. Subjects

Twelve healthy subjects (eight males; mean age: 31; range 22–48; right-handed; normal or corrected-to-normal vision) volunteered. They gave written informed consent according to the declaration of Helsinki.

2.2. Task

Subjects were comfortably seated in a Faraday cage, within a sound attenuated room. Subjects were performing a between-hand choice reaction-time (RT) task: they had to press a left or a right key with sufficient strength to produce the response (force threshold: 9,81 N corresponding approximately to 15% of a maximum voluntary contraction), with their right or left thumb, respectively, as fast and accurately as possible after a response signal (RS). RSs were even or odd numbers (3, 4, 6, 7) displayed in the center of a faradized video monitor (visual angle: 1.6°). The trial began with a white fixation cross in the center of the screen. This cross was turned off when the RS was presented. The RS was turned off by subject's response and the next one was presented 500 ms after. Between the response and the next RS, the fixation cross was presented again during the interval separating subjects' response and the presentation of the next response signal. If subjects did not respond within 800 ms, the RS was turned off and the next one was presented. RTs longer than 800 ms were discarded, and considered as omissions. A feed-back (beep) was given to the subject when the force threshold of his key press was crossed, and thus, that the required force to produce the response was sufficient. Half of the subjects had to respond to even and odd numbers by a right or a left button press, respectively. The other half performed the opposite stimulus-response mapping. After one training block (120 trials), each subject had to perform 4 blocks of 240 trials. Between each block, subjects could take a break at their convenience.

2.3. Data recordings

Variations of developed force were recorded by force sensors (Mescan LK-SS 50) placed in each response key (in each hand).

Electroencephalogram (EEG), electromyogram (EMG), and electrooculogram (EOG) were recorded continuously from preamplified Ag/AgCl electrodes (Biosemi® Active-Two electrodes®, Amsterdam). The signal was filtered and digitized on-line (bandwidth: 0–268 Hz, 3 dB/octave, sampling rate: 1024 Hz).

For EEG, 64 recording electrodes were disposed according to the