Electrophysiological indexes of the cognitive-motor trade-off associated with motor response complexity in a cognitive task

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ABSTRACT

Complex actions require more cognitive and motor control than simple ones. Literature shows that to face complexity, the brain must make a compromise between available resources usually giving priority to motor control. However, literature has minimally explored the effect of the motor response complexity on brain processing associated with cognitive tasks. Consequently, it is unknown whether carrying out a cognitive task requiring motor responses of increasing complexity could reduce cognitive processing keeping stable motor control. Therefore, this study aims to investigate possible modulations exerted by increasing motor response complexity in a cognitive task on brain processing. To this aim, we analyzed the event-related potentials and behavioral responses during a cognitive task with increasing complexity of the required motor response (key-press, reaching and stepping). Results showed the increasing motor complexity enhances early visual and attentional processing (P1 and N1 components) but reduces the late post-perceptual cognitive control (P3 component). Additionally, we found a component following the P3 which was specific for stimuli requiring a response. This component, labeled N750, increased amplitude along with the response motor complexity. Behaviorally, response accuracy was not affected by complexity. Results indicated that in cognitive tasks stimulus processing is affected by the complexity of the motor response. Complex responses require a greater investment of early perceptual and attentional resources, but at late phases of processing, cognitive resources are less available in favor of motor resources. This confirms the idea of the motor-priority cognitive-motor trade-off of the brain.

1. Introduction

Voluntary movements have different degrees of complexity. Complexity can be defined by the number of dimensions involved in motor activity such as the number of joints involved or the movement degrees of freedom (Cordo and Gurfinkel, 2004). From this point of view, multi-joint actions present an intrinsic complexity and represent an effective way of studying the central nervous system in a quantitative and experimentally verifiable manner (e.g., Hogan et al., 1987). Complex voluntary movements are characterized by the involvement of the entire body; they require coordination and intentionality and need anticipatory postural adjustments (e.g., Cordo and Gurfinkel, 2004). Just as the output of the movement involving multiple muscles and joints is complex, so is the control exercised by the brain (e.g., Hogan et al., 1987).

Many behavioral studies have shown that the complexity of motor response may influence cognitive processes and associated performances. Henry and Rogers (1960) hypothesized that the time to initiate a response increases as the programming process becomes longer and more complex. This hypothesis was confirmed by Christina and Rose (1985) measuring the premotor time (the time from a movement triggering stimulus to the first change in the muscle electrical activity) in three arm actions of increasing complexity, which were produced in response to an acoustic signal. The results showed that, compared to the simplest task, the premotor time became progressively slower for the tasks requiring an increasing number of moving joints. More recently, it

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has been shown that response time, errors, and movement effectiveness were modulated by movement complexity (simple lifting vs. complex reaching). This effect could be attributed to a top-down strategy aimed at increasing efficiency for the actions most prone to developing kinematic errors (Gálvez-García et al., 2018). In general, when examining the relationship between motor response complexity and cognitive functions, there is a good agreement that the more complex the action, the greater the cerebral load is required (e.g., Floyer-Lea and Matthews, 2004; van der Veer et al., 2024).

At the brain level, neuroimaging studies indicated that premotor and dorsal parietal areas are selectively activated as the complexity of movements increases providing evidence of the participation of these areas in the integration of motor and spatial attributes during the selection of movements (Deiber et al., 1991; Grafton et al., 1992; Wexler et al., 1997; Zimmermann et al., 2012). In addition to this anatomical data, event-related potential (ERP) studies identified the timing of the brain activity associated with movement complexity. Hackley and Miller (1995) demonstrated that the lateralized readiness potential (LRP) enlarged as finger movement complexity increased. The same complexity effect has been shown by Stief et al. (1998) suggesting that complex movements require parallel programming of more effectors. The motor preparation phase indexed by the Bereitschaftspotential (BP) increased as a function of complexity indicating that motor complexity may be encoded in premotor areas (for reviews Shibasaki and Hallett 2006; Di Russo et al., 2017). Also, the contingent negative variation (CNV) amplitude directly depends on movement complexity. Instead, movement complexity seems not to affect CNV in imagined actions, probably because execution requires a greater cognitive complexity than imagination (Kranczioch et al., 2010). A limitation of these studies is that they considered finger movements, without involving other effectors and used self-paced movements. Recently a study of our research group implemented a cognitive visuo-motor discriminative response task (DRT) requiring as a motor response three movements of increasing complexity involving additional body parts (keypress, reaching + keypress, and stepping + reaching + keypress). Results confirmed the modulation of the BP as a function of the complexity in the premotor cortex but, in addition, we also found larger preparatory activity in the parietal and visual areas for the reaching and stepping condition, respectively (Casella et al. 2024). ERP studies investigating the effect of motor complexity on reactive brain processing, i.e., the brain response to stimuli triggering movements of different complexity, are rare. A study comparing ERP obtained in an auditory oddball task between simple (keypress) and more complex (reaching + keypress) responses, found no effects on the studied components N2 and P3 (Lalo et al., 2005). However, (Reiser et al., 2019, 2021) investigated the ERP evoked by an auditory oddball task while the participant had to concurrently complete various outdoor motor tasks. They consistently found, in the late stage of cognitive processing in parietal areas a decrease in the P3 component amplitude for more complex movements. This result was interpreted as a reduction of the available cognitive resources as the motor complexity increases and indicated the key role of attention in cognitive-motor tasks (Reiser et al., 2021). On the other hand, Papin et al. (2024), investigating cognitive-motor interference in naturalistic environments found no P3 effects suggesting that the motor or cognitive skills of participants may affect the outcome with less P3 effect in trained individuals.

Since the literature on brain processing of stimuli requiring increasing motor response complexity is scarce, the following questions remain. If attention plays a key role, can a stimulus triggering motor responses of different complexity affect early visual and attentional processing? The literature on motor complexity provides evidence in support of a cognitive/motor trade-off. Specifically, in tasks requiring a simple motor response, more cognitive and fewer motor resources are deployed, conversely, for complex motor responses, less cognitive and more motor resources are implemented by the brain (e.g., Reiser et al., 2021). The decrease of post-perceptual cognitive processing indexed by the P3 reduction for more complex response movements has been associated with this cognitive/motor trade-off. If this trade-off is real, besides the P3 reduction, we should also find a concurrent amplification of motor-related activity. Indeed, in the literature, this claim is approved as well such as the brain balancing the activation patterns of two mental processes by varying the task's complexity thanks to its feature of incorporation, realigning, or formation of new neural connections (e.g., Lucia et al., 2023). If this trade-off is real, besides the P3 reduction, we should also find a concurrent amplification of motor-related activity.

Considering all the evidence reviewed so far, the present study was aimed at investigating the interaction between the complexity of the motor response in a cognitive task and the brain processing of the stimulus triggering the response. To this aim, we used the same visuo-motor DRT and response modalities used by Casella et al. (2024) since that task evokes large early visual and attentional components such as the P1 and the N1, and large late components such as the P3 (for normative ERP data in that DRT see Di Russo et al., 2019). In addition, the response modality of increasing difficulty used by Casella et al. (2024) was able to produce distinct patterns of preparatory activity indicating the suitability of those response movements.

If the motor response requirements of a DRT interact with early visual processing and attention, we should find modulation of P1 and N1 early ERP components. Moreover, to confirm the existence of a cognitive/motor trade-off, for more complex motor responses we should find a concomitant reduction of the cognitive P3 component and increased brain activity associated with motor processing.

2. Methods

2.1. Participants

The sample size for this study was determined with the G*power 3.1.9.2 software (Faul et al., 2009). We set the power calculation for a 3 × 2 repeated measures ANOVA design (specified in the statistical analysis section) at 90 % with an α=0.05. These computations showed a minimum of 19 participants to reach the effect size of 0.28, taken from the minimum partial eta square of the ERP results of a previous study using a similar experimental ERP design (Mussini et al., 2020). Therefore, 20 volunteers (mean age 23.4 ± 1.4 years, 6 females, 14 males) among the students of the "Foro Italico" University were recruited to participate in the study. Inclusion criteria were the following: absence of chronic somatic problems, absence of any neurological and psychiatric disorders, absence of any medication, and normal or corrected-to-normal vision. All participants were not informed about the aim of the study and were right-handed. Each participant gave his informed consent before participating in this study in accordance with the Declaration of Helsinki after that all procedures were performed in compliance with relevant laws and institutional guidelines and have been approved July 27th, 2023, by the research ethics committee of the University of Rome "Foro Italico" reference number 0146–23.

2.2. Stimuli and procedure

The experiment was carried out at the Laboratory of Cognitive and Action Neuroscience, at the University of Rome "Foro Italico". Participants were tested in a low-lit, sound-attenuated room. They were positioned in front of a computer screen, such that the initial distance between their eyes and the screen was 114 cm. As shown in Fig. 1, the discrimination response task (DRT) was made up of four different visual stimuli, but only two out of four were 'target' or 'Go' stimuli and the participant had to provide a response (consisting of pressing a key). The other two were 'non-target' or 'No-Go' stimuli requiring no response. The stimuli consisted of (4 × 4°) square configurations containing horizontal and vertical lines. Each run consists of 80 trials equally divided between target (40) and non-target stimuli (40). Each stimulus has the same probability of presentation ($p = 0.25$). The order of stimuli
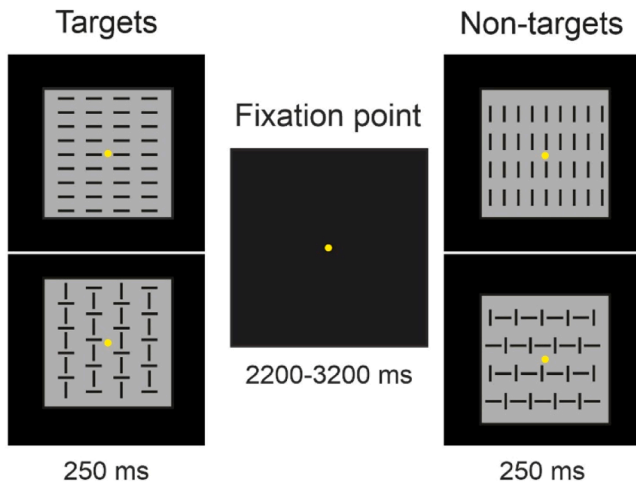
Fig. 1. Representation of the DRT stimuli and timing used in all conditions.

presentation was randomized both within the single run and between the different runs, to avoid learning effects. The stimulus duration was 250 ms and the inter-stimulus interval varied from 2200 to 3200 ms to prevent stimulus prediction and ERP overlaps with previous and following stimulus. A central fixation point (diameter $0.15 \times 0.15°$) was always present during the run.

The DRT was performed in the following three different conditions (Fig. 2): In the "*Keypress*" condition participants were seated on a chair in front of a desk and the response pad was placed on the desk approximately 30 cm away from their body. The participant executed the task with the right index finger already positioned on the response button and they were asked to limit their body movements. They were asked to keep their feet firmly on the ground maintaining a straight posture and avoiding muscle contractions.

- In the "*Reach*" condition participants were in the same position as in the "Keypress" condition, but the button was at a greater distance from their body, but such that it could be reached by stretching the right arm. This distance varied according to the length of the participant's arm (50–55 cm). Once the button was pressed, the arm returned to the starting position.
- In the "*Reach-Step*" condition participants were standing and the button pad was placed on a 90 cm tall support at a distance such that it could be reached by taking a step forward and simultaneously stretching the right arm. The distance from the keyboard varied according to the participant's arm length and step (75–80 cm). Participants were instructed to always perform the step with the right leg and not to lift the heel of the left foot off the ground.

Each condition consisted of 10 runs and each run contained 20 trials per each of the four stimuli with a total of 800 trials per condition (400 target and 400 for non-target stimuli). The duration of a single run was 3′40′′. In the middle of each condition a 2-minute break was allowed. An additional 5-minute break followed each condition. The duration of each condition was approximately 40′, while the total duration of the experiment was approximately 130′. In all conditions, the response was a keypress made with the right index finger on a response pad. Participants were instructed to respond as quickly as possible, without neglecting accuracy. The condition order was counterbalanced among participants. Before the EEG recording, a minute of warmup (about 20 trials) was allowed to familiarize with the task.

Note that these three experimental conditions and the DRT task were the same as those used in a previous study of this group (Casella et al. 2024) analyzing pre-stimulus ERP components in a distinct set of participants.
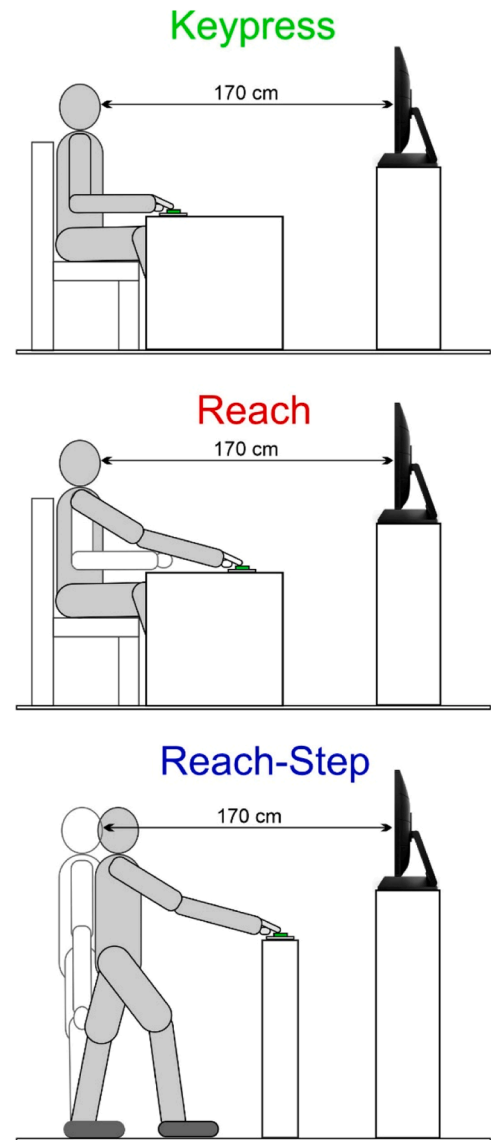

Fig. 2. Representation of response modality in the three conditions.

2.3. Behavioral data

Accuracy and response times in the DRTs were measured. Accuracy was defined as the percentage of errors (i.e., responses not provided to the target stimuli and responses provided to the non-target stimuli) out of the total target and non-target trials delivered. Both speed and accuracy were required to participants, and no time limit was imposed for the response. However, none of the participants had outlier response time or accuracy.

2.4. EEG recording and analysis

The participants were tested using a 64-channel EEG system (Brainamp™ amplifiers) with active electrodes (Acticap™) and software (Recorder 1.2 and Analyzer 2.2) all by BrainProducts GmbH (Gilching, Germany). The sintered silver electrodes were mounted according to the 10–10 International System and referenced to M1 and then off-line re-referenced to the M1–M2 average. Horizontal and vertical electrooculograms (EOG) were monitored by bipolar recordings, with electrodes positioned at the left and right external canthi (HEOG) and below and above the left eye (VEOG). The EEG was digitized at 250 Hz, amplified (bandpass of 0.01–60 Hz including a 50 Hz notch filter, 2° order), and

stored for offline averaging. The signal was then filtered with 0.1 Hz high-pass and 40 Hz low-pass 2° order filters.

The EEG was segmented in epochs starting 200 ms before the stimulus onset (time 0) and finishing 1700 ms after and processed to reduce ocular artifacts using the propagation factor algorithm available in the Analyzer software. Furthermore, automatic artifact rejection was performed before signal averaging to discard epochs contaminated by signals exceeding the amplitude threshold of ±80 μV, and on average 4.2 % of trials were rejected. The artifact-free trials were averaged, and amplitudes were measured to the −200/0 ms baseline.

To identify the intervals and electrodes to quantify the ERP components, "the "collapsed localizer" method (Luck and Gaspelin, 2017) was used. Based on this method, the three conditions and two trial types (target and non-target) were averaged, and the global field power (GPF) was calculated. The GFP describes the ERP spatial variability considering all scalp electrodes and allowing a reference-independent descriptor of the ERP. The GPF peaks were used to identify the main ERP components and an interval around the peak was used a-priori to establish the interval of analysis of each component. As done in previous studies (e.g., Aydin et al., 2024) an interval based on 80 % of the peak power is reasonably optimal to identify the component range. Using these parameters the following four intervals of analysis were identified: 120–156 ms, 192–224 ms, 412–564 ms, and 690–788 ms. To identify the electrode pool to insert in the analyses, in each of the mentioned intervals, the electrode with the maximum amplitude and the electrode with an amplitude within 80 % of the maximum were included in the pool. According to this procedure, for the first and the second intervals six electrodes were included (PO7, PO8, PO3, PO4, P7, and P8) defining a bilateral "Parieto-Occipital" pool identifiable in the P1 ERP component in the first interval and the N1 in the second. For the third interval, six electrodes were included (CP1, CPz, CP2, P1, Pz, and P2) defining a medial "Centro-Parietal" pool identifiable in the P3 component. For the fourth interval, five electrodes were included (AFz, F1, Fz, F2, and FCz) defining a medial "frontal" pool identifiable such as a frontal late negativity component hereafter defined as N750.

To have an idea of the N750 origin, the source localization of the ERP activity in the 690–788 ms interval was achieved using the "exact low-resolution brain electromagnetic tomography" (eLORETA) software (freely available at www.uzh.ch/keyinst/loreta.htm) to compute the cortical three-dimensional distribution of current density. This method utilizes a discrete, three-dimensional distributed, linear, weighted minimum-norm inverse solution. The weights applied in eLORETA confer precise localization capabilities to test point sources, generating current density images with exact localization, albeit with a limited spatial resolution. Notably, eLORETA demonstrates no localization bias, even in the presence of structured noise, representing an advancement over LORETA and its standardized version, sLORETA (Pascual-Marqui, 2002).

2.5. Statistical analysis

After checking for normality and homoscedasticity of the distribution of the variables, the statistical analysis used for the behavioral data (response time and accuracy) was a repeated measure analysis of variance (ANOVA) with the Condition as a 3-level factor (Keypress, Reach, and Reach-Step). For the ERP data, a 3×2 repeated measures ANOVA was used for each interval/component. considering the Condition (Keypress, Reach, and Reach-Step) and Trial type (Target and Non-target) as factors. The alpha threshold was set to 0.05. The partial eta squared (η_p^2) was reported as a measure of effect size. To reduce the likelihood of Type 1 errors, the Bonferroni post hoc test was used to report the corrected p-values. The software used for statistical analysis was Statistica 11 (StatSoft Inc., Tulsa, OK, USA).

3. Results

3.1. Behavioral data

The ANOVA carried out on the response times showed a significant effect of condition ($F_{(2,38)}=242,6$, $p < 0.001$, $\eta_p^2=0.987$). Post-hoc comparisons showed that the Keypress condition response time (535 ms SD=37) was lower ($p < 0.001$) than the other two conditions. The Reach condition response time (970 ms SD=127) was lower ($p < 0.001$) than the Reach-Step condition (1236 ms SD=190).

Regarding accuracy, the ANOVA showed a non-significant effect of condition ($F_{(2,38)} \leq 1$). The error rate was low, being on average 1.7 % (SD=1.6).

3.2. ERP data

The ERP waveforms of the three pools of electrodes in the three conditions and for the two trial types are shown in Fig. 3. The scalp topography in the four selected intervals is shown in Fig. 4 for target trials. The earliest component was the P1 peaking at 140 ms and showing a positive bilateral parieto-occipital distribution. The P1 was similar and equally modulated by the condition for both trial types. The N1 peaked at 200 ms and analogously to the P1 showed a bilateral parieto-occipital distribution but of negative polarity. The N1 was comparable for the target and non-target trial types but appeared modulated by condition. The P3 peaked around 480 ms with a positive medial parietal distribution. The P3 was larger for target trials than for non-target trials and was modulated by the condition for target trials only. Finally, a negative late component (N750) peaked around 750 ms over medial frontal areas. The N750 was larger for target trials than for non-target trials and was modulated by the condition for target trials only.

Fig. 5 shows the mean amplitude and variability of the studied components. The ANOVA on the P1 showed a significant effect of the Condition ($F_{(2,38)}=3.6$, $p = 0.037$, $\eta_p^2=0.158$) and post-hoc comparisons indicated that the Reach condition was larger ($p = 0.033$) than the Keypress condition. The other comparisons were not significant ($p > 0.540$). The effect of Trial type ($F_{(1,19)}=3.9$, $p = 0.085$, $\eta_p^2=0.148$) and the interaction ($F_{(2,38)}<1$) were not significant.

The ANOVA on the N1 showed a significant effect of the Condition ($F_{(2,38)}=3.7$, $p = 0.033$, $\eta_p^2=0.164$) and the post-hoc comparisons indicated that Reach-Step condition was larger ($p = 0.032$) than the other two conditions that did not differ each other. The effect of Trial type ($F_{(1,19)}<1$) and the interaction ($F_{(2,38)}<1$) were not significant.

The ANOVA on the P3 showed a significant effect of the Condition ($F_{(2,38)}=8.7$, $p < 0.001$, $\eta_p^2=0.957$) and post-hoc comparisons indicated that in the Keypress condition, the amplitude was larger ($p < 0.011$) than the other two conditions that did not differ each other. The effect of Trial type ($F_{(1,19)}=4.7$, $p = 0.043$, $\eta_p^2=0.545$) was also significant showing a larger amplitude for the target trials. However, the interaction was significant ($F_{(2,38)}=4.1$, $p = 0.024$, $\eta_p^2=0.237$). Post-hoc comparisons showed that the significant differences found for the main effect were confirmed for target trials only ($p < 0.05$). For non-target trials, the P3 did not differ among conditions.

The ANOVA on the N750 showed a significant effect of the Condition ($F_{(2,38)}=4.3$, $p = 0.020$, $\eta_p^2=0.186$) and post-hoc comparisons indicated that in the Reach-Step condition, the amplitude was larger ($p < 0.009$) than the other two conditions. In addition, the amplitude of the Reach condition was larger ($p < 0.007$) than the Keypress condition. The effect of Trial type ($F_{(1,19)}=5.2$, $p = 0.034$, $\eta_p^2=0.215$) was also significant showing a larger amplitude for the target trials. The interaction was significant ($F_{(2,38)}=7.9$, $p = 0.001$, $\eta_p^2=0.302$). Post-hoc comparisons indicated that for the target trials in the Reach-step condition, the amplitude was larger ($p < 0.001$) than the other two conditions and that the amplitude of the Reach condition was larger ($p < 0.001$) than the amplitude of the Keypress condition. For the non-target trials, no
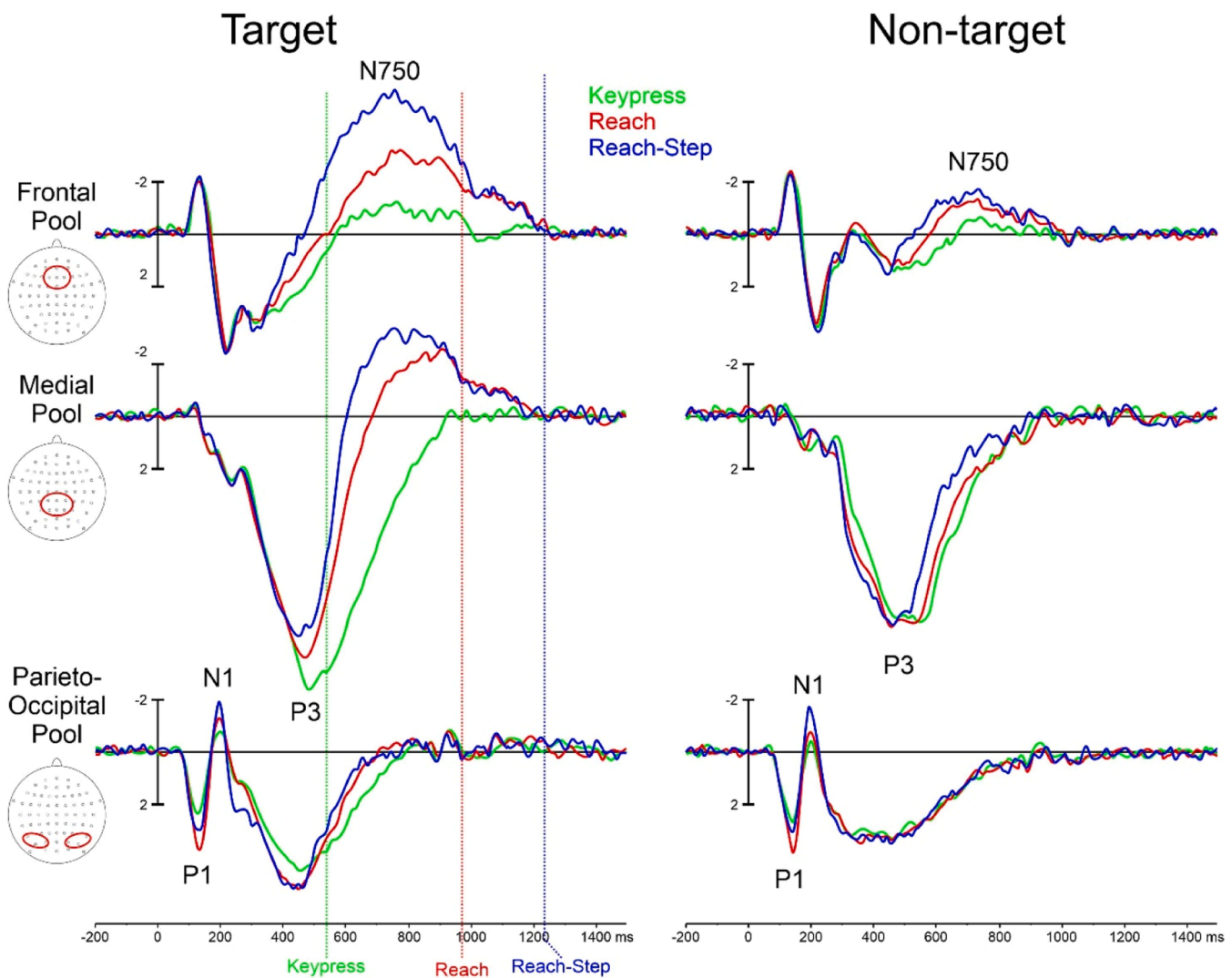
Fig. 3. ERP waveforms in the three conditions. The colored vertical lines indicate the response time. The circles within the head representation indicate the electrodes included in the pool.

significant differences were present.

The source localization of the N750 for target trials is presented in Fig. 6. The brain is represented from a frontal view. The activity seems to rise bilaterally from the medial frontal and prefrontal cortex. The contribution of the prefrontal cortex is more evident in the Reach and Reach-Step conditions than in the Keypress condition. The areas more active were the inferior, middle, and superior frontal gyri.

4. Discussion

Motor responses of different complexity degrees should influence in different ways the brain processes necessary to carry out a cognitive task. However, while we know that performing motor actions using different effectors activate different neural substrates (Heed et al., 2011; Pitzalis et al., 2019; Bellagamba et al., 2022), the literature is scarce about the influence of motor responses involving different body parts on a cognitive task. Based on these issues, the objectives of the present study were to verify: 1) if visual and attentional processing depends on motor response complexity; 2) if the balance between cognitive and motor resources employed for the same task is influenced by the motor response complexity.

The behavioral data were as expected since the response time was the longest in the Reach-Step condition, the shortest in the Keypress

condition, and intermediate in the Reach condition. This is compatible with the necessary time required to implement the motor response. As motor complexity increases, the duration of the movement itself increases, and therefore the time necessary to carry it out. No effect of the motor response complexity was observed on accuracy.

ERP data showed that the P1 amplitude was larger in the Reach condition compared to the Keypress condition. The P1 component is known to reflect the processing of basic stimulus features (e.g., Di Russo and Spinelli, 1999; Zhang and Luck, 2009) and is affected by tasks requiring arm movement towards peripersonal (Eimer et al., 2006; Gherri et al., 2009; Gherri & Eimer, 2011) and personal space (Job et al., 2017). Here, results confirm that stimuli triggering reaching actions may require stronger visual processing than stimuli triggering simple key presses. This is not confirmed by the Reach-Step condition, which even if containing the reach action and being slightly larger than the Keypress condition, did not reach the significance. An explanation for this lack of effect could be that in the Reach-Step condition, the stepping and reaching combination may have reduced the effect.

The N1 was larger in the two more complex tasks compared to the simple keypress. The N1 has been previously associated with early attentional processing (e.g., Di Russo et al., 2019). This result confirms the hypothesis that more complex actions require larger attentional resources. Reaching and stepping responses may require large attentional
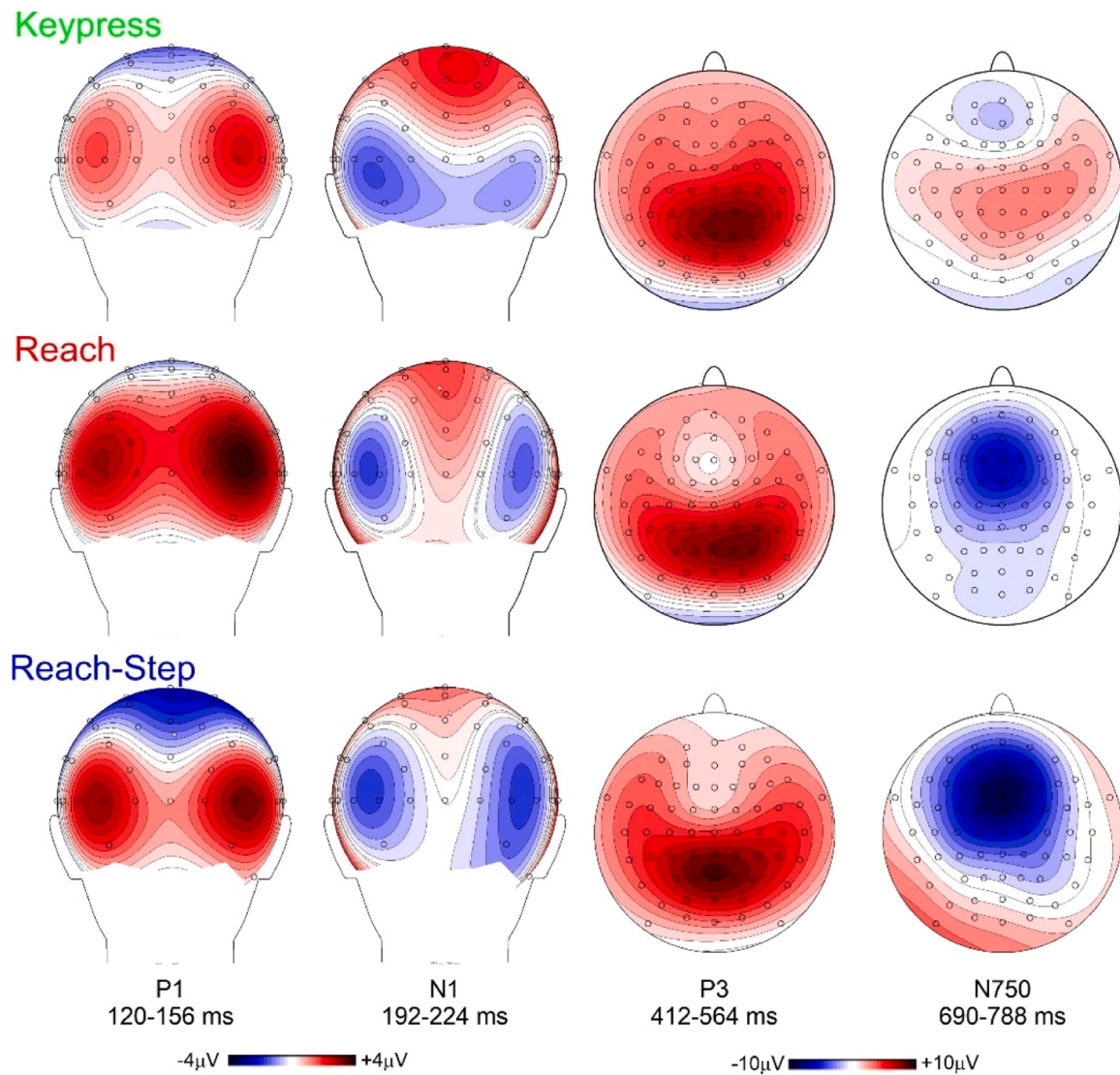
Fig. 4. Scalp topography of the studied components for target trials in the four considered intervals. For the P1 and the N1, a posterior view is displayed, while for the P3 and the N750, a top-flat view is shown.

control likely to take into consideration both the objects' position (the press-button position) and the effectors' position required for the response. The association of the N1 with the attentional controls of objects' and effectors' positions has been shown in Wascher et al. (2009) and Mason et al. (2015), respectively. They proposed that the N1 would be representative of a dynamic attentional processing system of the surrounding environment aimed at improving the efficiency of the action. From this point of view, compared with the Keypress, the Reach and the Reach-Step conditions require greater coordination of the effectors involved, and greater sensorimotor integration, and therefore seem to require a larger effort in terms of early visual attention. Extending these findings to the results of the present study, it can be deduced that the response motor complexity induces brain adaptations that modulate the mechanisms underlying the attentional orientation towards stimuli triggering motor responses. Considering that the N1 was larger in the two standing positions (Reach and Reach-Step condition) than the sitting position (Keypress), Another data interpretation could be that the N1 was affected by the posture and not the task. However, Bhat et al. (2022) found no differences in any early visual ERP when comparing sitting and standing positions. Overall, since no systematic differences were found among the three conditions, we can safely affirm that the N1 amplitude is modulated by different variables and that the

complexity of the action may be one of these.

An alternative, but not exclusive, interpretation of the P1 and the N1 effects could be that they represent a general heightened level of arousal when the movement is more than a keypress.

Results on the P3 showed that in the task with the simplest response motor response modality, the amplitude was larger than in those with a more complex response modality. This result confirms the hypothesis that a lower complexity of the motor response allows greater cognitive resources available. Reiser et al. (2019) reached similar conclusions in an auditory oddball task during the simultaneous execution of motor tasks of increasing difficulty. Reiser and coworkers interpreted the P3 effect as a reduction of the amount of resources available for carrying out the cognitive task during a concurrently complex motor task.

A similar result was obtained by Matthews et al. (2006) comparing ERP evoked by single with dual-task conditions and finding reduction of the P3 evoked by target stimuli in dual task. In addition, neuroimaging studies have also found a reduction in parietal activation during the simultaneous execution of visual/auditory cognitive tasks and motor tasks (Just et al., 2001; Rèmy et al., 2010).

In tasks as the present DRT (or Go/No-go task), the P3 reflects post-perceptual cognitive processes such as decision-making and context updating regarding whether to emit or not the motor response (e.g.,
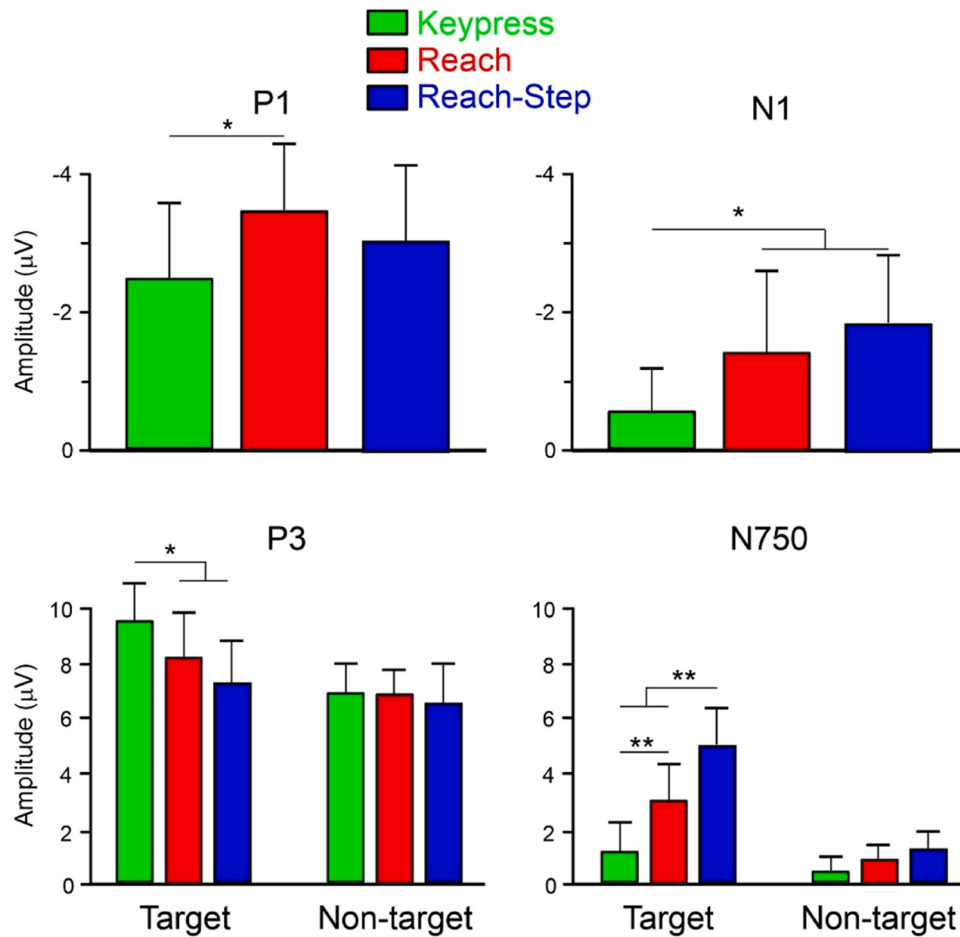
Fig. 5. Amplitudes of the studied components and their variability expressed as standard deviation. For the P1 and the N1, the main effect of the condition is reported since the effects of trial type and the interaction were not significant. The significant differences are also indicated (*$p < 0.05$, **$p < 0.01$).
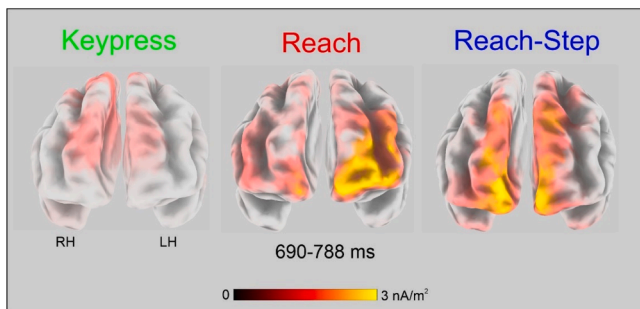

Fig. 6. Source localization of the N750 for target trial in the three conditions and in the 690–788 ms interval (RH=right hemisphere LH=left hemisphere).

Gajewski and Falkenstein, 2013; Smith et al., 2008). The P3 therefore seems to represent the end of a cognitive period, the closure of a perceptual cycle in which certain stimulus features are paid attention regarding the relevance of the stimulus for the task (e.g., Falkenstein et al., 1995; Gajewski and Falkenstein, 2011, Verleger, 1988). Following this literature, in the present study, it can be deduced that in addition to the decision-making, the P3 for target trials, may also reflect a further process linked to motor response complexity.

In addition to the mentioned ERP components that we initially aimed to investigate; we also found another wave over frontal sites. This component had a negative polarity and peaked at about 750 ms and was therefore labeled N750. For target trials, this component was well detectable and was modulated by the motor response. For non-target

trials, the N750 was small and independent from the response modality. The N750 seems not connected with response time since the peak latency did not change among conditions even though the relative response time varied consistently. All these features led us to think that this wave could express the motor controls necessary to initiate a complex action. To the best of our knowledge, this component was never reported in Go/No-Go tasks as the present and hardly in other cognitive tasks where the last activity is typically the P3 (see Di Russo et al., 2019 for normative data on this task). However, some studies on brain-computer interface (e.g., Lytaev and Vatamaniuk, 2021) described several minor negative components following the P3 (the N450, N750 and N900) using visual oddball tasks. These waves were smaller than the previous negativity such as the N1 and were prominent over the parieto-occipital areas. These were linked to mechanisms of "exhaustive search" to categorize the incoming information. The topography and the interpretation of these late negativities do not correspond to the present N750. Another component labeled N700 is instead known in the literature but was found in linguistic tasks and has been associated with the retrieval of semantic memories within the prefrontal cortex (e.g., Adorni and Proverbio, 2012; Barber et al., 2013). Therefore, that component could be hardly associated with the N750 found here.

A possible explanation for the lack of data on this late component could be explained by its feature being clearly recognizable for target trials only and in tasks requiring a more complex response modality than a simple keypress. As pointed out in the introduction, there are no studies using those complex response modalities in feature discrimination tasks to study the considered ERP components. Moreover, Bender et al. (2006), studying the timing of post-movement motor processing in

simple and alerted reaction time tasks, identified a post-movement negative prefrontal component (negative post-imperative motor variation) that occurred approximately 400–500 ms seconds after key press. However, this component is observable only when the interstimulus interval is sufficiently long and may be associated to the learning of motor sequences.

The presence and the modulation of the N750 are in line with the hypothesis we made about the cognitive/motor trade-off of brain functions (e.g., Plummer et al., 2013). According to this view, if the motor demands of a cognitive task increase, fewer cognitive resources are invested by the brain (reduced P3), and more motor resources are instead deployed (larger N750) to correctly execute the action. This phenomenon is also observable in cognitive-motor dual-task paradigms, in which cognitive resources must be distributed across the task (Malcolm et al., 2015; Vasquez et al., 2016). The source localization of the N750 seems to confirm this proposal since the frontal cortex is strongly involved in motor control. Among the various possible trade-off scenarios (e.g., Plummer et al., 2013), the one found here seems to be a *motor-priority trade-off* since less cognitive resources are used in favoring motor resources.

A possible confounding factor of this study could be that the instruction for the most complex task (Reach-Step) may have increased the cognitive load of participants and affected the result. However, considering that before the EEG recording 20 trials of warmup (about one minute) were allowed to familiarize with the task. We think that it is unlikely that this simple instruction increased the cognitive load since all subjects were right-handed, therefore, the Reach-Step action came naturally to them, in addition, the press button was positioned in the direction of the arm and hand used to respond. These precautions made the execution of the instruction relatively simple and automatic. For a limited number of trials (estimated at 1–2 % of trials), subjects did not comply with the instruction slightly lifting the hill of the left foot. In this case, the instruction was repeated at the end of the run, as many times as necessary lightening the memory load.

Future studies could consider other types of movements and even more complex cognitive and motor tasks to test the limits of motor and cognitive control. Furthermore, the effect of other variables could be evaluated, such as the degrees of freedom allowed by the movement, the hand and leg dominance, the magnitude of environmental distraction, and the level of motor and/or cognitive expertise since Papin et al. (2024) indicate that these factors may affect brain processing during cognitive/motor task.

5. Conclusions

In this study, three motor responses of increasing complexity to the same cognitive task were compared. We observed that if the response modality is more complex than just a button press and requires additional reaching and stepping movements, the brain resources used for the motor and the cognitive task vary as a function of motor complexity. In particular, late cognitive processes in parietal areas indexed by the P3 were suppressed for stimuli requiring complex actions. However, as in a motor-priority cognitive/motor trade-off system, activity rising from motor-related brain areas progressively increased probably to reinforce the motor control over the initiated action.

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CRediT authorship contribution statement

Bianca Maria di Bello: Writing – review & editing, Writing – original draft, Project administration, Investigation, Formal analysis, Data curation. **Andrea Casella:** Writing – review & editing, Writing – original draft, Project administration, Investigation, Data curation. **Merve Aydin:** Writing – review & editing, Investigation. **Stefania Lucia:** Writing – review & editing, Visualization, Investigation. **Francesco Di Russo:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Funding acquisition, Conceptualization. **Sabrina Pitzalis:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

I have nothing to declare.

Data availability

Research data and codes will be made publicly available on Mendeley after the acceptance.

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