Research article

Motor planning and performance in transitive and intransitive gesture execution and imagination: Does EEG (RP) activity predict hemodynamic (fNIRS) response?

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HIGHLIGHTS

- RP peak amplitude was higher for transitive than intransitive gestures.
- RPs produced a "facilitation effect" (anticipated peak) for transitive gestures during imagination.
- PMC supported the execution process and the PPC was implicated in transitive gesture execution.
- RP was a predictive factor in modulating the hemodynamic brain activity (fNIRS) during action production.

ARTICLE INFO

ABSTRACT

The interplay between neural structures and processes underlying motor planning and proper movement initiation and guidance is still a matter of debate. The present study aimed at investigating cortical correlates of motor planning and production when execution and imagery of real-life gestures are performed, with an additional focus on potential specificities of meaningful transitive/intransitive gestures. Electrophysiological (Readiness Potential – RP) and functional near-infrared spectroscopy (fNIRS) measures were analyzed to investigate the relationship between processes supporting action planning, execution and imagination. Participants were instructed to observe videos presenting various gestures and then to execute or to imagine them. We observed comparable RP before gesture execution and imagination, with a "facilitation effect" of transitive gestures in particular for imagination. Further, while the supplementary motor regions showed similar O_2Hb profiles during both execution and imagination of transitive/intransitive gestures, premotor and posterior parietal areas showed specificities respectively for execution processes and transitive gesture execution. Finally, regression analyses showed that RP amplitude is a predictive factor of subsequent hemodynamic brain activity during action production. Such predictive role was modulated by both task and gesture type factors.

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1. Introduction

It is known that a complex network of neural structures is responsible for voluntary action intentionalization and execution, including the supplementary and pre-supplementary motor areas (SMA, preSMA), the premotor cortex (PMC), the primary motor cortex (MI), the anterior cingulate cortex (ACC), posterior parietal areas (PPC), and subcortical structures. Specifically, basal ganglia, PMC and prefrontal areas send inputs to the preSMA, and the subsequent interaction between preSMA, SMA and pre-/motor areas are thought to support intentional planning and to generate the ensemble of neural events that lead to movement initiation [1]. Gesture production is then mediated by the information exchange between the ACC-preSMA-SMA system and MI. Further, action production and guidance are supported by an additional network where MI acts as a pivot and receives inputs from sensory areas through intermediate connections between parietal and premotor structures, which are thought to primarily guide object-oriented transitive actions, in addition to the main contribution by cerebellum [2].

Preparation and planning of intentional actions have also been associated to a specific movement-related cortical potential [MRCP,

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[3]] – the Readiness Potential (RP). Such deflection slowly rises before voluntary actions (even if simulated or planned but not executed), and it is constituted by two subcomponents: an early slow segment – referred to as early-RP or RP – and associated to preSMA, SMA and premotor activity; and a steeper segment – referred to as late-RP or negative slope (NS') – occurring around 500 ms before movement and associated to the activity of contralateral premotor and motor areas. The NS' was found to be modulated by specific characteristics of the movement that is planned, such as its precision and complexity [4]. It has been observed that goal-directed actions present also a parietal distribution of the RP components [5].

However, the relationship between action planning and production has been scarcely analyzed, with studies mainly focusing on differences between enacting or imaging a gesture [6,7] or differences between kinds of actions, e.g. transitive and intransitive ones [8].

As for the comparison between types of task, in line with the simulation theory [9], motor imagery, execution, and observation proved to share many representational, electrophysiological and functional correlates [10–13]. Nevertheless, when focusing on the intentionalization and preparation phase, both motor imagination and execution engage supplementary and prefrontal areas but, interestingly, dynamic causal modeling studies showed that the SMA also modulates contralateral primary motor structures thus leading to both actual action initiation and suppression of motor activity when the prepared action has not to be produced, as is the case of imagined gestures [14,15].

As for the comparison of planning and production of transitive vs. intransitive gestures, the role of the presence of an object on gesture planning and its neural signature are still matters of debate. Indeed, only a few studies investigated such points with respect to gesture production and it was globally shown that transitivity may affect brain activity during motor performance [8,13,16].

Recently, functional near-infrared spectroscopy (fNIRS) have been used to further explore neural mechanisms underlying motor functions [8], given its greater usability and portability and its lower invasivity with respect to other imaging techniques [17]. Taking into account neural correlates of upper limb movements, fNIRS was successfully used to investigate hemodynamic activity during simple movements execution [6,18–20], action observation [21,22], and motor imagery [7,23].

The present study was then devised to approach the question concerning correlates of motor planning and production phases by using a multi-measure integrated EEG/fNIRS approach. In particular, the predictive role of intentional planning (as measured by EEG RP measure) on subsequent brain activity (as measured by fNIRS hemodynamic modulations) linked to execution vs. imagination of transitive vs. intransitive gestures. It is worth noting that, differently from previous studies, we focused on complex real-life hand gestures (e.g. painting and waving goodbye) so to increase the ecological validity of observations. Indeed, our everyday activities and inter-personal communications do not simply ground on simple motor acts like to ones that have been traditionally used to investigate movement processes (e.g. finger movements), but are supported by articulate actions with complex motor programs that are flexibly and intentionally adapted to the context and to the presence of other inter-agents [24].

Specifically, we expected to observe: i) similar NS' over precentral sites before both execution and imagination; ii) a positive association between electrophysiological correlates of planning and premotor-sensorimotor activity during execution and imagination of gestures, with stronger associations in case of execution with respect to imagination; iii) grater activation of premotor and sensorimotor areas during gestures execution than imagery; iv) earlier NS' maxima during planning of transitive gestures with respect to intransitive ones; v) greater activation of parietal areas for transitive compared to intransitive gestures, since parietal areas were found to support object-function representations [8,25].

2. Methods

2.1. Participants

15 volunteers (11 female; M_{age} = 32; SD = 7.1; range = 24–42) took part in this study. All participants were right handed, had no history of neurological, psychiatric or motor disorders, and had normal or corrected-to-normal vision. All subjects gave written informed consent and the study was approved by the local Ethics Committee (Department of Psychology, Catholic University of Sacred Heart, Milan) in accordance with the ethical standards of the Declaration of Helsinki.

2.2. Procedure

Participants sat in front of a computer screen. Before experimental sessions, they were trained to perform the experimental tasks when the words 'Execute' or 'Imagine' appeared on the screen after the presentation of a video. The familiarization session lasted a few minutes. Familiarization gestures were different to those used in the experimental session so to avoid potential learning biases. Videos showed a right arm enacting transitive/intransitive gestures from first-person view. During execution (E) participants had to perform the action they have previously observed. During imagination (I) they had to imagine performing the action they have previously observed. To further check timing, participants were instructed to signal the end of executed/imagined movements by pressing a button.

Experimental tasks were counterbalanced and gestures were randomized (E-prime2 software, Psychology Software Tools, Inc., Sharpsburg, PA, USA). A total of 96 trials were divided in three sessions. Transitive and intransitive gestures were equally presented within each session. 16 transitive and intransitive gestures were chosen from an unpublished validated stimuli set on the bases of familiarity, frequency, complexity, transitivity, and preferred laterality ratings by 28 judges (Balconi & Bartolo, *unpublished*) and were randomly repeated during experimental sessions. All reproduced gestures could be performed with one single hand and were performed with the right hand. The gender of the actors was counterbalanced so to avoid gender-biases.

2.3. EEG recordings and data reduction

A 16-channel portable EEG system (V-Amp, Brain Products GmbH, Gilching, Germany) was used for data acquisition. An NIRS-EEG compatible cap with Ag/AgCl electrodes was used to record EEG from scalp sites referred to earlobes: F3, Fz, F4, FCz, FCC5 h, FCC6 h, Cz, CCP5 h, CCP6 h, CPP3 h, CPP4 h, PPO5 h, PPO6 h, O1, and O2 (10/10 International System). Data were sampled at 1000 Hz and recorded with an input bandpass filter (0.01–100 Hz) and a 50 Hz notch filter. Electrodes impedance was always kept below 5 kΩ. A 0.1–30 Hz bandpass filter was applied offline to EEG data in order to reduce noise. Ocular artifacts were corrected by a regression-based correction algorithm. After visual inspection for residual artifacts, only artifact-free trials were considered and included in subsequent averaging and analyses (no less than 40 epochs per condition). On the basis of previous literature and of preliminary morphological analyses, the late-RP amplitude (base-to-peak values) and latency (time of occurrence of the maximum amplitude) data were quantified by identifying the amplest negative deflection rising within the 500-ms pre-onset window. The epoch onset was coincident with
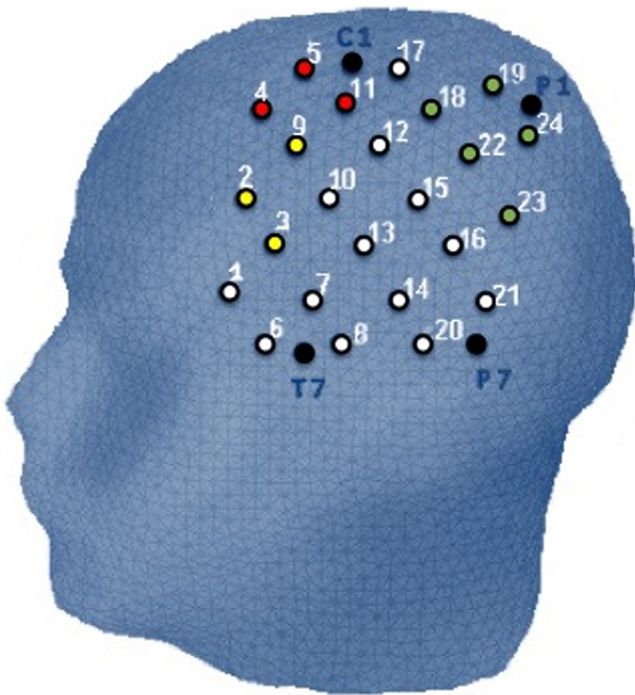
Fig. 1. fNIRS channels positions and corresponding cortical areas, left hemisphere. Numbers identify channels; analyses focused on yellow (PMC), red (SMA) and green (PPC) channels. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the beginning of the executed task (gesture execution or imagination) and the baseline window was set from 1200 ms to 1000 ms before such onset. The identification of peak data was guided by a semiautomatic weighted detection algorithm so to minimize detection biases due to the potential occurrence of multiple local maxima owing to noise or jittering. The outcomes of the detection algorithm have then been manually verified and adjusted were needed taking into account the morphology of specific response profiles. Electrophysiological profiles were computed for a specific region of interest broadly corresponding to supplementary/premotor structures [26] (channels F3, FCz, FCC5 h).

2.4. fNIRS recording and analysis

In order to evaluate changes in hemodynamic activity (O_2Hb-HHb) over the cerebral cortex during E and I tasks, we collected fNIRS data using a continuous wave system (NIRx Medical Technologies, LLC. Los Angeles, CA, USA; sampling rate: 6.25 Hz), with a 24-channel array of optodes placed over sensorimotor regions according to the 10/10 International System positions. Refer to Fig. 1 for channels positions and corresponding cortical areas [26].

Acquired data have been processed offline on the basis of wavelengths and sensors location to obtain change values of O_2Hb and HHb concentration for each channel (scaled in mmol∗mm). Preprocessing of the fNIRS raw signal included visual inspection and rejection of artifacts (rejection criterion: amplitude of hemoglobin [Hb] signal N ± 5 SD) and filtering (band-pass filter: 0.01-0.3 Hz). Subsequently, task-related mean concentration of O_2Hb and HHb for each trial and each channel was calculated based on a 5-s window (1–6 s after the task onset). We also calculated the baseline O_2Hb/HHb concentration during a trial-specific 5-s window. Task-related and baseline measures were then used to compute trial-specific differential indices – d-values. The d-values were computed as the difference between baseline (m_1) and task-related (m_2) mean hemoglobin concentration divided by the standard deviation of baseline measures (SD_1): $d = (m_1-m_2)/SD_1$. The use of derived indices (such as the d-value) allows for a proper comparison between conditions and across subjects and prevents interpretation biases due to inter/intra-individual differences in fNIRS raw changes values.

Statistical analyses were applied to the d-values for both O_2Hb and HHb concentration. Since the HHb analyses did not reveal significant effects, we will report only O_2Hb results.

3. Results

3.1. Phase I – EEG data

NS' amplitude and latency data were entered into two-ways repeated measure ANOVAs including task (E *vs.* I) and condition (transitive *vs.* intransitive gesture) as main factors. Type-I errors associated with inhomogeneity of variance were controlled by decreasing the degrees of freedom using the Greenhouse-Geisser epsilon. Post-hoc comparisons with Bonferroni correction for multiple comparisons were successively applied to the data.

As for NS' amplitude, the interaction effect between task and condition was found to be significant ($F(1.14) = 11.04$, $P = 0.001$, $\eta^2 = 0.42$), whereas no main effect reached significance threshold. Post-hoc comparison highlighted a decrease of NS' amplitude for intransitive with respect to transitive gestures in I ($F(1,14) = 6.13$, $P = 0.001$, $\eta^2 = 0.28$) but not in E. Moreover, peak amplitude was lower for intransitive gestures in I than E ($F(1,14) = 7.102$, $P = 0.001$, $\eta^2 = 0.30$) (see Fig. 2), whereas no significant difference was found for transitive gestures.

As for latencies, the task x condition interaction effect was again significant ($F(1,14) = 9.39$, $P = 0.001$, $\eta^2 = 0.40$), and task and condition main effects did not reach significance threshold. Specifically, latency was reduced for transitive compared to intransitive gestures in E ($F(1.14) = 7.55$, $P = 0.001$, $\eta^2 = 0.31$) and in I ($F(1,14) = 6.90$, $P = 0.001$, $\eta^2 = 0.29$).

3.2. Phase II – fNIRS

Statistical analyses were applied to d values. Specific ROIs have been computed and related to left SMA (channels 4-5-11), left PMC (channels 2-3-9), and left PPC (channels 18-19-22-23-24). We then ran a repeated-measure ANOVA model including task (E *vs.* I), condition (transitive *vs.* intransitive gesture) and ROI (SMA, PMC, PPC) as main factors. A significant main effect was found for task ($F(1,14) = 5.11$, $p < 0.05$; $\eta^2 = 0.28$) with increased O_2Hb levels during E with respect to I. No other main effect or two-ways interactions were statistically significant. The three-way interaction instead reached the significance threshold ($F(2,28) = 6.04$, $p < 0.05$; $\eta^2 = 0.27$). Going down to specifics (see Fig. 3), we firstly found a greater increase of O_2Hb for transitive gestures ($F(1,14) = 5.98$, $p < 0.05$; $\eta^2 = 0.25$) and for intransitive gestures ($F(1,14) = 6.67$, $p < 0.05$; $\eta^2 = 0.27$) in E with respect to I within the PMC. Secondly, a relevant increase of O_2Hb was found for transitive with respect to intransitive gestures in E ($F(1,14) = 6.11$, $p < 0.05$; $\eta^2 = 0.26$) within the PPC. No other simple effect was significant.

3.3. Phase III – EEG-NIRS regression analyses

To explore the relationship between electrophysiological markers of gesture planning and hemodynamic modulations related to their proper execution or imagination we performed regression analyses using the NS' amplitude as the predictor variable and d-values as the predicted variable. Distinct analyses were applied to E and I and transitive/intransitive gestures for each cortical area (PMC, SMA, and PPC). Corrections for multiple comparisons was applied to the analyses.
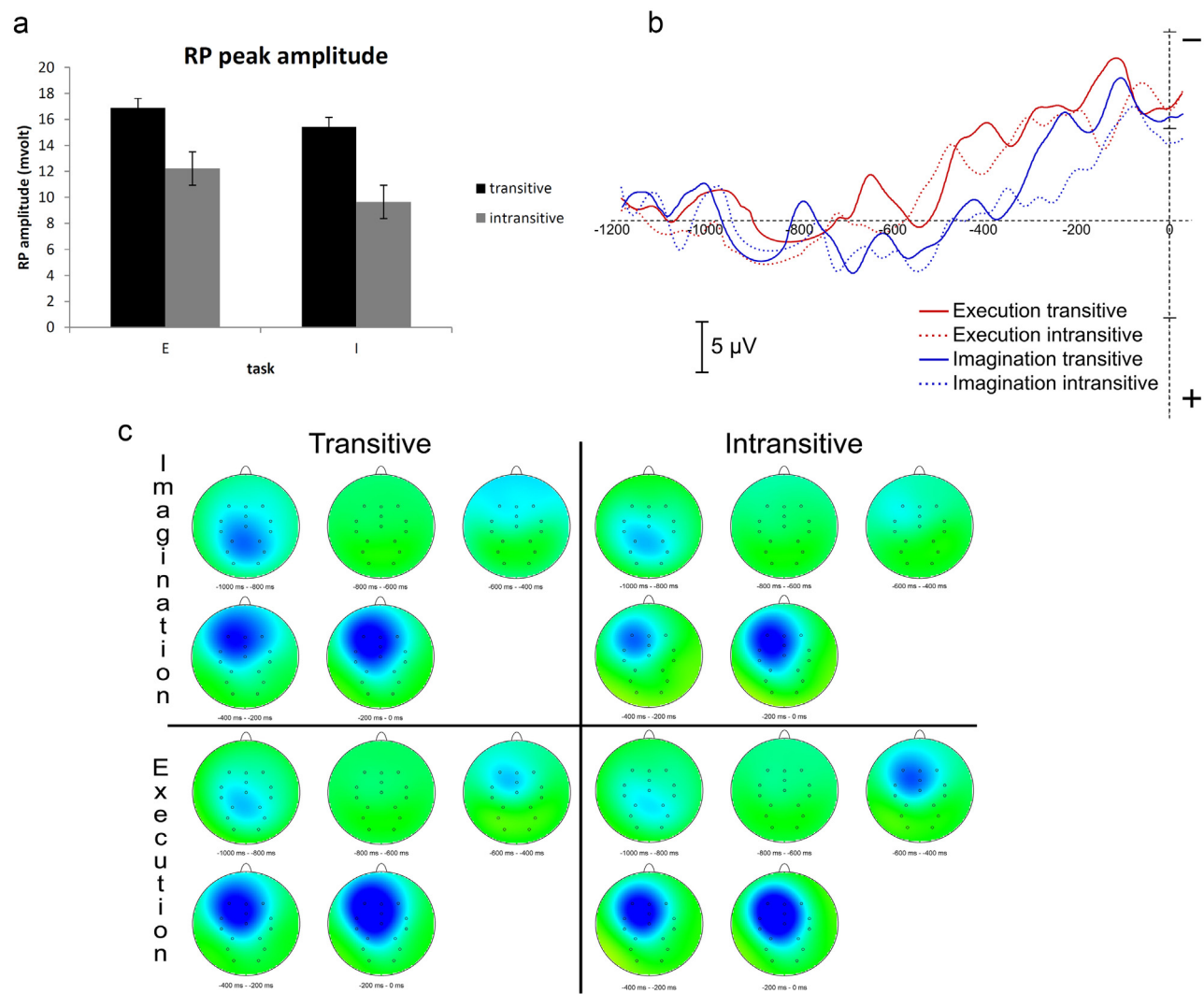
Fig. 2. Electrophysiological pre-movement activity as a function of transitive/intransitive gestures and execution/imagination (grand averages). a) NS' peak amplitude; b) waveforms; c) scalp maps.

Table 1

Regressions analysis: RP values as predictor variable and O2Hb as predicted variable in response to different tasks (E/I), cortical areas (PMC, SMA, PPC) and gesture types (transitive/intransitive).

	PMC		SMA		PPC	
	E	I	E	I	E	I
transitive						
R^2	0.40	0.19	0.47	0.49	0.49	0.16
β	0.33	0.38	0.35	0.22	0.36	0.37
std error	0.29	0.36	0.32	0.30	0.33	0.29
t	**2.95**[**]	1.07	**3.26**[**]	**3.31**[**]	**3.35**[*]	1.19
intransitive						
R^2	0.37	0.23	0.43	0.42	0.14	0.13
β	0.43	0.17	0.39	0.28	0.38	0.26
std error	0.28	0.38	0.25	0.35	0.41	0.33
t	**2.22**[*]	1.04	**2.99**[**]	**2.90**[**]	1.03	1.07

[*] $p = 0.05$.
[**] $p = 0.01$.

As shown by the analyses (Table 1), increasing NS' amplitudes predicted increasing *d*-values (mirroring cortical activity) within the SMA for both E and I with regard to both transitive ($R^2 = 0.47$, $p = 0.001$; $R^2 = 0.49$, $p = 0.001$) and intransitive ($R^2 = 0.43$, $p = 0.001$; $R^2 = 0.42$, $p = 0.001$) gestures. In contrast, NS' measures predicted *d*-values related to PMC with regard to transitive ($R^2 = 0.40$, $p = 0.001$) and intransitive ($R^2 = 0.37$, $p = 0.01$) gestures only for E. Finally, greater NS' amplitude predicted increased cortical activity within PPC only for E in case of transitive gestures ($R^2 = 0.49$, $p = 0.001$).

4. Discussion

4.1. NS' potential for gesture planning

The systematic presence of the RP in the planning phase of both execution and imagination tasks is, to our knowledge, the first demonstration of such a process. The crucial role of supplementary and premotor areas in generating pre-movement MRCP related to action planning and higher-order organization and preparation of voluntary movements was well-emphasized by previous studies [4,27]. Moreover, many previous studies have shown an important role of SMA in complex movements planning [28] and, again, of supplementary and pre-motor areas in both imagination and execution, in contrast with the specific contribution of motor cortices in action execution [29].

In addition, this is – to our best knowledge – the first study to directly compare execution and imagination of different gesture types, namely meaningful intransitive and transitive gestures.
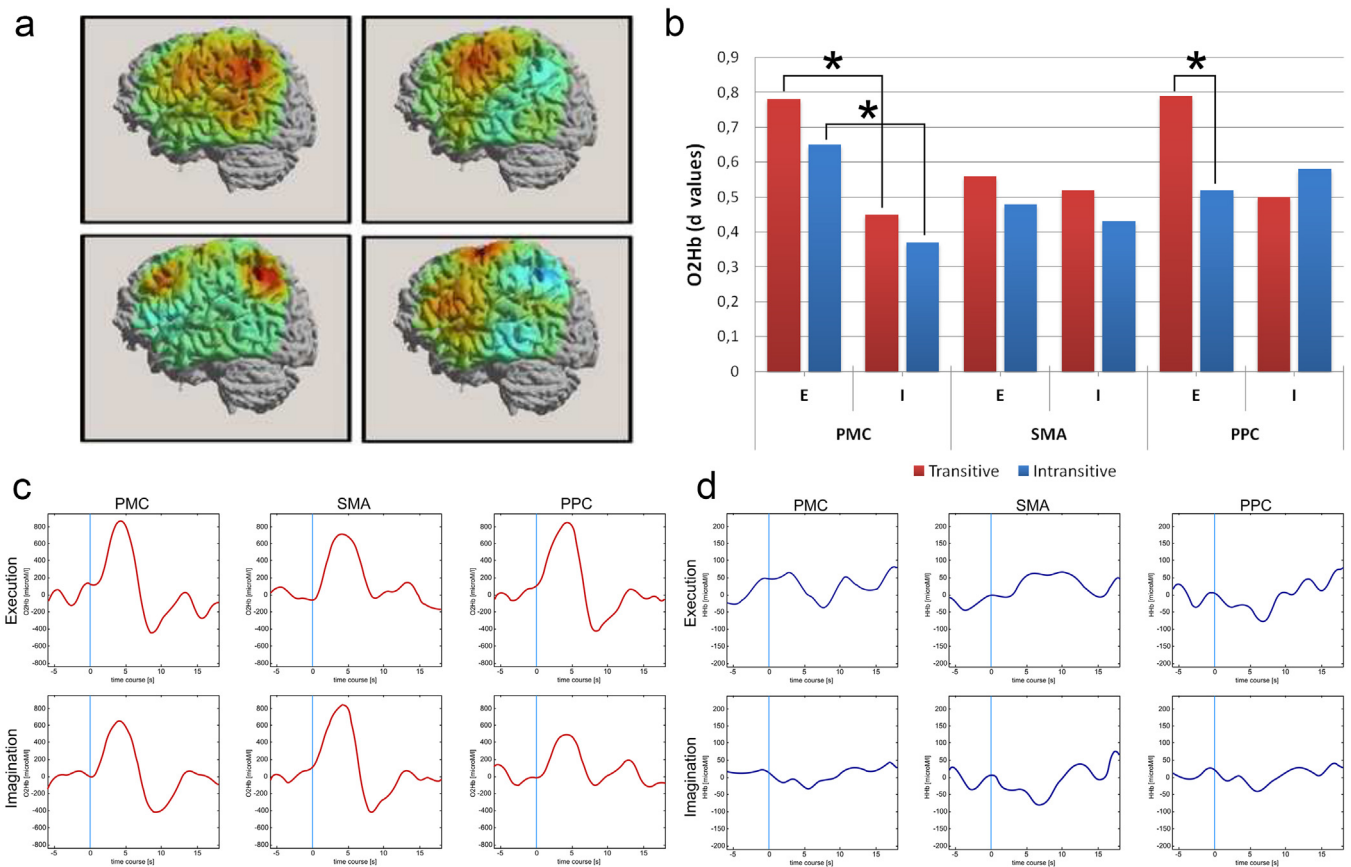
Fig. 3. Hemodynamic activity during experimental tasks. a) fNIRS cortical maps for E (top line) and I (bottom line) of transitive (left) and intransitive (right) gestures; b) O_2Hb modulation as a function of transitive/intransitive gestures and execution/imagination; c) O_2Hb response profiles for E(top line) and I (bottom line) in PMC, SMA and PPC (left to right); d) HHb response profiles for E(top line) and I (bottom line) in PMC, SMA and PPC (left to right).

Whereas the absence of significant differences in NS' amplitude between execution and imagination suggests a significant similarity of the intentional planning processes between these tasks, a consistent difference was observed depending on gesture type, with decreased deflections for intransitive gestures in particular before their imagination. Interestingly, latency measure supports this trend, with a consistent peak anticipation before transitive gestures. That anticipation might mirror a facilitation effect induced by the presence of the object and the goal-directed nature of the action (transitivity effect). This interpretation is in line with the sensitivity to object features and action affordances of the premotor-parietal network, which – in action preparation and guidance – may act as an intermediate station collecting internal and external sensory inputs for the integration with motor schemas and plans and transmitting them to the ACC-preSMA-SMA-MI network [2]. We may suggest that intransitive gestures implicated a reduced SMA-premotor activity for planning: since those areas are primarily involved in self-initiated movements and the implication of an object during motor planning may more largely require their contribution, present results may confirm the significance of transitivity for intentional planning. Nonetheless, we have to acknowledge that other areas may also contribute to action planning in case of a real action to be executed, such as posterior areas supporting object-related actions [5], even if we did not observe such posterior contribution.

It should be also noted that for the first time in the present study complex real-life gestures have been used to explore the transitivity/intransitivity specificities. Therefore, observed effects regarding supplementary/premotor electrophysiological correlates may be, at least partly, related to the complexity of gestures we used.

Indeed, literature showed that several factors are able to modulate the motor preparation process and, among these factors, the complexity of the movement plays an important role. For instance, even movements implying simple interaction with an object or relatively complex sequences of finger movements were shown to affect the onset and the amplitude of RP components [4,5]. However, about the nature of the gestures, human everyday activities and communication by gestures actually needs complex and finely planned actions. Therefore, by opting for real-life gestures, in the present study we increased ecological validity and we more directly were able to analyze action planning as it is developed in everyday behavior. Indeed, the gestures we selected replace common goal-directed actions that are frequently performed in everyday-life contexts (e.g. squeezing a sponge or cutting with scissors), or that are used to regulate social interactions (e.g. a beckoning gesture to invite someone to come nearer or a victory sign to celebrate something). Finally, complex meaningful gestures like the ones we used are pervasively used to shape interactions and convey meaning by accompanying and integrating verbal communication.

4.2. PMC, SMA and PPC for execution/imagination of transitive and intransitive gestures

Regarding the gesture production phase, relevant effects were found based on type of task and transitivity condition. Firstly, both PMC and PPC mainly supported the execution task, while SMA was similarly recruited during both gesture execution and imagination. Though the present data are partially in contrast with previous evidences [7,12], results are in line with the hypothesis that different action-related processes may generate partially different brain

responses [30]. In our case, imagining an action does not seem to identically activate the same left-sided network that is involved in the execution of the same gesture.

Secondly, executing transitive gestures proved to be more strongly associated with parietal posterior activity than the execution of intransitive gestures, and such difference was not observed during imagination. It has been underlined that parietal regions play a crucial role in execution of hand gestures, attention processes concerning limb movements, and their representation [13,16,31]. Previous fMRI and TMS studies suggested that the posterior parietal cortex comprises a mosaic of small areas, each specialized in guiding specific movements of the eyes, the head, the arms or the hands [32]. Further, for movements to be initiated, the motor and cognitive system must know the initial position of the body parts that have to be moved and the position of any external objects with which the body is going to interact, and has to integrate those information.

However, some critical considerations should be done about the specific (or aspecific) role of PPC in relation to the presence of action-related objects. Indeed, it is still a matter of debate whether the same areas play the same functional role in understanding/mediating actions that are produced in absence of an object. For example, parietal and premotor regions – thought to be part of a putative human mirror mechanism – seem to respond not only when people view object-directed actions (e.g. grasping) but to gestures as well. This is particularly interesting because it suggests that these areas might respond to the action *per se* rather than to object-related or contextual features. Present results point at the specific involvement of posterior parietal areas during execution of transitive gestures. Further, they suggest that object-directed and non-object directed actions may be mediated by partially different neuronal networks, and that parietal areas peculiarly mediate object-directed actions when complex gestures are actually performed.

4.3. EEG and fNIRS measures for gesture analysis

The NS' – as electrophysiological marker of motor planning – proved to predict subsequent brain activity during both gesture execution and imagination. Such predictive role was specifically elucidated by pre-central structures. The contribution of supplementary and pre-motor areas for motor planning and motor production was previously demonstrated using hemodynamic imaging *or* EEG investigation, but the direct influence of pre-movement electrophysiological variations on successive hemodynamic modulations was never explored before. Moreover, for the first time we tested and observed the predictive role of NS' amplitude on the active response of supplementary/premotor areas during action production, regardless of whether it was really performed or mentally simulated. In addition, NS' amplitude proved to influence the activity of PMC and PPC during real gesture execution. In other words, we may state that electrophysiological activity during motor planning affected the successive PMC and PPC responses when gestures were actually performed.

From another point of view, the present result could also be used to highlight the contribution of EEG measures in explaining hemodynamic responses (fNIRS). In this study, we chose fNIRS to measure brain activation related to representation of gesture. It was given evidence that the fNIRS is capable to measure brain activation related to different tasks including complex meaningful gestures, as it allows obtaining significant results in an ecologically-valid setting, during an upper hand movement study. Moreover, the optical imaging technique and the electrophysiological technique complemented each other taking respectively advantage of their high spatial and temporal resolution.

Nevertheless, limitations of our study have to be taken into consideration. First of all, the size of our sample and the number of trials might add limitations to the extent of conclusive remarks. Again, other relevant MRCP (such as premotor positivity) might be explored to obtain a more complete picture of the relationship between planning and motor performance phases. Furthermore, experiments investigating ipsilateral right hemisphere activity might offer additional hints on functional lateralization. Finally, even if – in the present experiment – some significant difference between transitive and intransitive gesture was observed, future research should better clarify the relationship between transitivity and object use, with more stringent comparisons between different kinds of transitive gestures.

5. Conclusions

To summarize, this study firstly confirmed the role of RP, for both gesture execution and imagination, in motor planning. Secondly, our results provided evidence that brain could differently recruit pre-central areas as a function of transitivity during gesture planning, with significant effects on RP peak amplitude and latency. Thirdly, consistently with previous findings, supplementary motor regions showed similar activations during proper gesture execution and imagination, while other premotor and parietal areas were differently activated depending on the type of task and gesture. Fourthly, NS' modulations proved to predict subsequent brain activity during gesture production as revealed by hemodynamic measures depending on both task an gesture factors.

Conflict of interest

The authors declare no competing financial interests.

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