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EEG features of the interaction between sense of agency and body ownership: a motor imagery BCI case study

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***Index Terms*—BCI, Motor Imagery, Virtual Reality, Extended Reality, Body Ownership, EEG, Neurofeedback, Gamification.**

The sense of body ownership, i.e., the experience of one's body as one's own, and the sense of agency, i.e., the feeling of control over bodily actions, are essential for bodily self-consciousness. Research on EEG-based brain-computer interface (BCI) has shown that individuals can retain a sense of agency and ownership even when they control virtual arms by imaging the movement but without physically performing it. Here, we investigated (i) if we are more accurate in controlling the movement of a virtual device qualified as part of one's own body and (ii) to what extent the EEG feature linked to the agency for one's own body parts and for external device differ. To this aim, participants use an EEG-based BCI to control two virtual arms presented either in a first-person perspective to induce both a sense of ownership and agency over the virtual arms, or in an anatomical incongruent position to retain only the sense of agency. Preliminary data (n=4) showed that there is no difference in the accuracy in controlling the virtual arms in the two conditions, as measured by the EEG decoding algorithm reflecting the motor intention of the user. Crucially, both conditions elicit a sense of agency over the virtual arms, although the sense of ownership was present only in the first-person perspective condition. If confirmed in the remaining participants to be tested (n=34), these results will suggest that the ability of controlling a virtual device is not affected by the sense of ownership felt over it. Therefore, motor control's accuracy and the subsequent sense of agency are the consequences of the association between an internal volitional signal and the external outcome, bypassing the actual body movements and the sense of body ownership. We provide a unique window into the relation between motor control and the sense of body ownership- findings that have important implications for daily life support of patients using neuroprostheses.

I. INTRODUCTION

When we move our body in space, we immediately feel that the body belongs to us. This feeling has been termed body ownership and refers to the experience of one's body as one's own [1]. At the same time, we also experience a sense of control for our actions, and for their consequences. The sense of controlling one's own motor acts, and through them, the events in the external environment has been termed sense of agency [2]. It is a common view that the sense of body ownership depends on multisensory integration. Information from different sensory signals (such as visual, vestibular, and auditory signals) reach cortical convergence zones in the frontal, parietal, and temporal lobes, where the integration of these body signals occurs [3] [4]. On the other hand, the sense of agency is experienced most clearly when there is a match between the predicted outcome and the actual outcome of an action [5]. According to this view, when an intentional motor command is issued, a "forward model" of the moving body estimates the sensory consequence of the action. Sensory prediction about the body and the environment is then compared with the actual sensory feedback of the action. If the efferent copy and feedback match, the movement has been performed as intended. If the perceived feedback clearly violates the expected outcome, then the participant becomes aware of this discrepancy and does not experience authorship of the action [6]. Disturbances of this comparator process have been suggested to underlie the abnormal experience of movements in pathological conditions. For instance, schizophrenic patients may have the feeling that their actions are not their own but are instead caused by external agents. Such symptoms arise from a failure to predict the consequences of self-generated actions. In the absence of appropriate predictions, sensory experiences that are caused by one's own actions are perceived as external events.

Although the sense of agency and ownership co-occur and correlate when we perform actions in the world, recent studies showed that it is also possible to dissociate ownership and agency in controlled experiments. For instance, healthy participants can perceive both ownership and agency for a virtual or prosthetic hand moving synchronously with one's own real hand. Placing the virtual/rubber hand in anatomical implausible position abolishes the sense of ownership for the fake hand, leaving intact the sense of agency [7]. This is not entirely surprising because, although the body is the

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normal vehicle of our actions, the human brain generates a sense of agency even with highly complex and indirect causal chains. Today, many actions that we carry out are mediated by computers and machines that modify the basic experience of performing an action through one's own body, extending the sense of agency from the experience of controlling one's own limb movements to the experience of controlling external events that are largely independent from the body [8].

This is particularly evident in the BCI where participants can control external devices, such as virtual avatars or neuroprostheses, by imaging the movement without physically executing it and bypassing the muscular system [9]. Recently, the impact of body ownership on motor imagery-based BCI was focused in [10]. This study combines BCI with virtual reality to modulate the level of body ownership and to enhance the sense of agency. Therefore, research on BCI showed that the absence of an actual movement does not reduce the feeling of agency, rather participants can experience agency as long as they feel active control over a virtual arm (see also [11]). Motor Imagery (MI), indeed, shares neural mechanisms with processes used in motor control [12]. Both in case of motor imagery and execution, similar electrical desynchronization phenomena can be observed on of the scalp just over the motor cortex. Motor imagery is widely exploited in BCIs as a way for control and communication between the brain and an external device [13].

Here, we want to clarify to what extent agency for a virtual avatar over which we have a sense of body ownership differs from the sense of agency for a virtual avatar over which we do not have a sense of ownership. To this aim, we used a motor-imagery BCI framework to study the electroencephalographic correlates of body ownership and sense of agency interaction. VR-based neurofeedback allows for an experiment aimed at separating body ownership versus sense of agency; at the same time, the BCI application domain allows for an EEG-based study of the interaction body ownership and sense of agency. An improvement in the performance of BCI users in the case of body ownership could indicate that the same features used for motor imagination detection are candidates for the EEG-based study of the interaction between body ownership and sense of agency.

II. Materials and methods

To understand the effect of ownership on sense of agency we created an interactive EEG based BCI-system using a virtual environment (see below) in which participants imagine to move two virtual arms in order to controll them and to perform a game. We compared the Body ownership condition (BO), in which the virtual arms were presented in a first person perspective, with a Non-Body Ownership condition (NBO), in which the virtual arms were presented in a implausible third person perspective.

A. System Implementation

1) Virtual environment and game

The virtual environment and the game were developed using Unity (version 2020.3.27f1). The immersive VR experience is delivered through HMD HTC VIVE PRO EYE[1] from HTC Corporation Inc. This is a virtual reality visor with a 3.5-inch diagonal dual-OLED display (2880 x 1600 pixel resolution), 90 Hz refresh rate and 110° field of view. To provide an immersive interaction with the environment, SteamVR Unity plugin was used, which provides the necessary resources for virtual reality and allows the developed application to be compiled and distributed.

The VR experience is supported by a simple gamification add-on consisting of two virtual limbs presented in a first-person-view (BO condition) or in a third-person-view (NBO) holding up a miniature football field. The 3D models of the field, arms and table top were modelled using the open source software Blender.

a

b

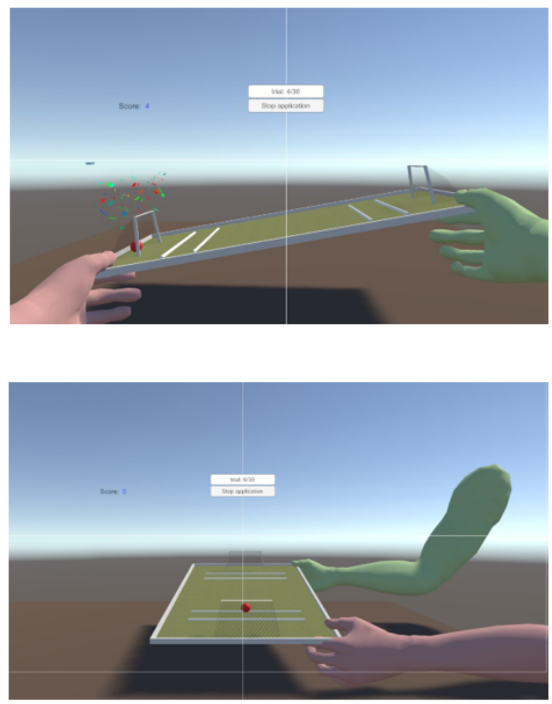

Fig. 1. VR MI football match in FPV (BodyOwnership condition) (a) and in 3PV (Non-BodyOwnership condition) (b). The virtual arm flashing green indicates the direction to be imagined in the Motor Imagery task.

At the start of the test, the ball is placed in the centre of the playing field and will be free to slide to the opposite side if the table is tilted. The participant will be asked to imagine (via an input of the virtual limb flashing green) the movement of the right or left arm, which will lead to the virtual arm lifting, the table tilting and the ball sliding towards the opposite goal (Fig. 1). On the software side, this process is facilitated by the use of Unity's integrated physics engine, which provides a very useful set of components for simulating physical phenomena. The objective is to get score in the opposite side goal of the court as many times as possible, even overcoming a couple of bumps in the proximity of each penalty area. As will be seen in the next paragraph, the more accurate the classification of the imagined movement, the greater the

[1] https://www.vive.com/us/product/vive-pro-eye/overview/

amplitude of the movement of the limb and, therefore, all the physical consequences in terms of speed, acceleration and the additional thrust on the ball to get it over bumps. The goals scored are shown progressively to the user; each point scored is followed by a sound and visual effect.

2) EEG acquisition

The FlexEEG headset by Neuro-CONCISE Ltd [2] was used for EEG data acquisition and digitization and transmission. 3 differential channels were implemented by means to six electrodes over the motor cortex. In particular, electrodes are located at FC3-CP3, FCZ-CPZ, and FC4-CP4 by following the standard 10–20 system for EEG recordings [14]. The ground electrode is placed at AFz. Conductive gel was applied below all the electrodes. Data were transmitted by means Bluetooth 2.0 protocol. The high wearability of the FlexEEG allows its integration with the VR visor (Fig. 2).

B. Participants

Four healthy participants (2 women; mean age: 32.75) with normal or corrected to normal vision provided written informed consent to take part in our pilot experiment, that was approved by the local ethics committee of the University of Naples II.

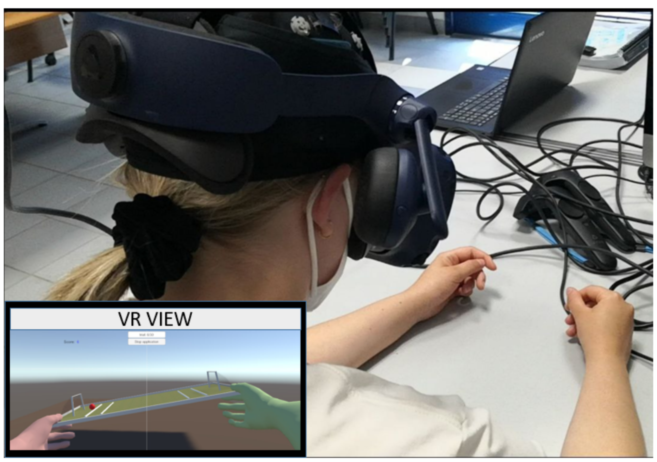

Fig. 2. VR MI football match experince. Thanks to its wearable design, FlexEEG was properly embedded with the VR HMD.

C. Experimental protocol

Participants performed both the BO and NBO conditions in two different sessions of 30 minutes, taking place in two different days. The order of BO and NBO conditions conditions was randomized across participants. Each session consisted of three blocks of trials for the system calibration and three blocks of the real VR neurofeedback in a gamification scenario. Each block consisted of 30 trials, therefore participants performed a total of 180 trials in each session. Between the two phases, the participant benefits from a break of 10 minutes. Each task (in both the calibration and neurofeedback phases) was based on imagining left or right arm movement according to a predefined random (in order to avoid any bias) sequence.

In the calibration phase, participants sit in front of a PC screen with the EEG equipment fitted. A left or right arrows appeared on the screen (i.e., the starting cue) and participants were asked to imagine to move their right or left arm depending on the arrow direction. Timing diagram for each individual trial in the online feedback phase is shown in Fig.3. In a synchronous BCI MI, the system processes the ongoing EEG signal in predefined time windows where motion imagery has occurred and discards the signal elsewhere. A cross validation method was used to find the optimal window in which the highest classification accuracy and the smallest difference in per-class accuracy was obtained. The optimal window was chosen by exploiting a $2.00\,\mathrm{s}$ wide sliding window with $0.25\,\mathrm{s}$ shift within the $3.00\,\mathrm{s}$ motor imagery window. Hence, this optimal window was considered for the training of the algorithm.

After the calibration phase, participants wear a virtual reality visor for the VR neurofeedback phase. In this phase, participants perform the game described in section II-A1. Two virtual arms appear on the VR scenario and, as a starting cue, one of the two arms randomly start to flash green. The aim of the game is to raise the flashing virtual limb to slide the ball from its starting position towards the opposite goal. The higher the rating score, the greater the height to which the virtual limb rises and, consequently, the acceleration of the ball towards the goal. A pair of bumps in the proximity of the penalty area prevent the task from being too easy for the user, motivating them and stimulating their sustained attention. To avoid user frustration, an artificial boost is given to the ball when a low-score causes the ball to stop on the bumps. At the end of each task, virtual limbs and table return to the starting position and the ball is repositioned in the midfield. The VR neurofeedback phase using the developed game was based on a BCI based on synchronous motor imagery. In a synchronous BCI MI, the system processes the ongoing EEG signal in predefined time windows where motion imagery has occurred and discards the signal elsewhere.

At the very end of each sessions, participants were asked to complete a 12-statements questionnaire to assess the ownership and agency sensed over the virtual arms, using a 7-point Likert scale ranging from - 3 (strongly disagree) to 3 (strongly agree). Three statements referred to the feeling of ownership, and three statements described sensations related to agency. The remaining six statements served as a control for suggestibility, task compliance and expectancy effect. Three statements served as a control for ownership and three for the agency (See Table III). The statements were adapted from previous studies [7],[11]

D. Signal processing

The pipeline for EEG signal processing is composed by a (i) Filter Bank (FB) composed by an array of bandpass filters from $4\,\mathrm{Hz}$ to $40\,\mathrm{Hz}$, (ii) a common spatial patterns (CSP) block for feature extraction, (iii) the mutual information-based best individual features (MIBIF) block to select the most

[2]https://www.neuroconcise.co.uk/

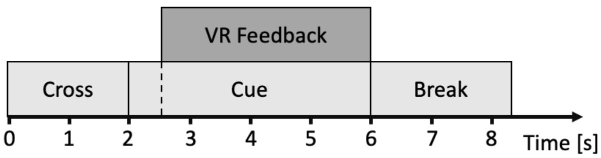

Fig. 3. On-line feedback phase protocol.

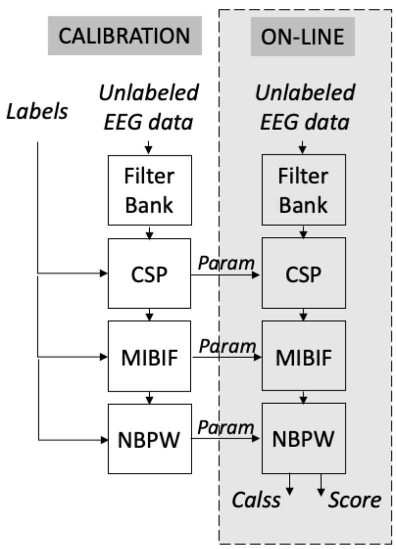

Fig. 4. Calibration and on -line operation of FBCSP algorithm. CSP: common spatial pattern, MIBIF: mutual information-based best individual features, NBPW: naive bayesian parzen window.

important features, and (iv) finally, a Naive Bayesian Parzen Window (NBPW) classifier. Specifically, the classifier provides a class and its associated probability. These were exploited to modulate neurofeedback during the on-line phase. The same pipeline is used for on-line and off-line signal processing. Both signal acquisition and processing are implemented through a Simulink model whose outputs feed the Unity application. The on-line operation is preceded by a calibration phase based on Matlab scripts. These scripts allow to calculate optimal parameters values of CSP, MIBIF and NBPW to maximize classification accuracy during on-line EEG signal processing. Matlab scripts are also used to analyse signals after the experiments. In offline analyses, baseline removal was first applied by considering the $100\,\mathrm{ms}$ before the cue. The block diagram of the algorithm is showed in Fig. 4

III. Results

A. Classification performance

From EEG tracks, $2.00\,\mathrm{s}$-wide epochs were extracted every $0.25\,\mathrm{s}$ (overlap $= 1.75\,\mathrm{s}$). The epochs were classified by applying a 5-folds cross validation with 10 repetitions. As an example, in Fig. 5 the average accuracy is reported for the Session 1 (feedback) of subject 1, at varying the epoch end-time-of-acquisition.

Best accuracies are reported for each subject in Tab. I for the body-ownership based task (gray) and the non body-ownership version (white), respectively. Each session and phase are considered separately.

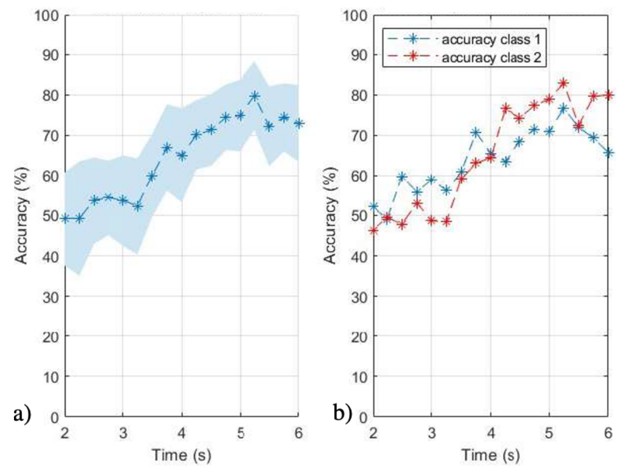

Fig. 5. Average accuracy of subject 1 during the first test session. The best average accuracy is reached after 5.250 s.

Accuracy (%)

	Session 1		Session 2	
	calibration	feedback	calibration	feedback
S01	85	79	69	64
S02	60	55	57	72
S03	54	54	64	72
S04	72	62	60	62
mean	62	75	64	74

TABLE I
BEST MEAN ACCURACY FOR EACH SUBJECT IN THE SUBSEQUENT SESSIONS. IN GRAY, THE SESSION WITH NEUROFEEDBACK BASED ON BODY OWNERSHIP.

The two system versions can be compared by referring to the two inter-subject mean accuracies. It can be noted that the one associated with the feedback phases based on body-ownership resulted higher of about $10\,\%$ with respect to the non body-ownership version.
Regarding the participants score, the subject who scored the most goals overall and first in the rank (*SO2*, with 64 goals) is also the one who showed the best average classification accuracy.

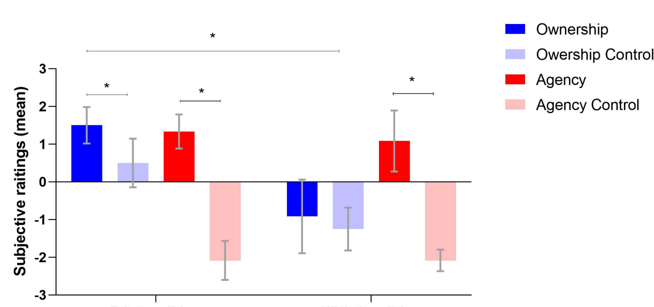

Fig. 6. Dissociation between ownership and agency. The graph shows the average ratings for each question as a function of the BO and NBO conditions. Asterisk mark a significant difference. Error bars indicate standard error of mean.

Assessment	Statement
Ownership	Q1. I felt like I was looking at my own hands, rather than virtual hands
	Q2. I felt as if the virtual hands were part of my body
	Q3. I felt as if the virtual hands were my hands
Ownership Control	Q4. I felt as if I had more than two arms
	Q5. I felt as if my hands had disappeared
	Q6. I felt as if my hands became virtual
Agency	Q7. I felt as if I could cause virtual hand movements
	Q8. I felt as if I could control virtual hand movements
	Q9. The virtual hands were obeying my will and I could make them move exactly as I wanted.
Agency Control	Q10. I felt as if the virtual hands controller my will
	Q11. It seemed as if the virtual hands had a will of their own
	Q12. I felt as if virtual hands were controlling my movements

TABLE II
THE STATEMENTS USED TO ASSESS THE OWNERSHIP AND AGENCY. EACH STATEMENT WAS RATED ONCE PER CONDITION (BO AND NBO). THE STATEMENTS WERE RATED ON A 7-POINT LIKERT SCALE FROM (-3) TO (+3). THERE WERE THREE STATEMENTS ASSESSING THE SENSE OF BODY OWNERSHIP AND THE SENSE OF AGENCY RESPECTIVELY, AS WELL AS THREE CONTROL STATEMENTS FOR BOTH THE SENSE OF OWNERSHIP AND AGENCY

B. *Performance and behavioral results*

First of all, we assessed the agency and ownership felt over the virtual hands in the two sessions. To this aim, we computed the mean score from each of the three ownership statements, and a mean score from the three agency statements. Similarly, we computed average scores of the corresponding control statements. In this way, four single scores were computed: “Ownership”; “Agency”; “Ownership control” and “Agency control”. We used the non-parametric Wilcoxon test for pair-wise comparisons to compare both ownership and agency score with their control statements in the same condition and to compare ownership and agency categories between the two conditions. Despite the small sample size, in the BO condition the “Ownership” category (1,50, SD: 0.96) was significantly different from its control category (0.5; SD: 1.29; p=0.0452). Crucially the ”Ownership” ratings in the BO condition were significantly higher than the ”Ownership” scores in the NBO condition (-0.916, SD = 1.95 ; p = 0.021), suggesting that participants perceived ownership for the virtual hands only in the BO condition, i.e., when the virtual hands were presented in a first person person perspective as compared to when the hands were rotated. In the BO condition, there was also a significant difference between ”Agency” category (1,333 SD: 0.902) and its control category (-2,0833; p= 0.0317), but, most importantly, there was no significant difference between the ”Agency” categories between the BO and NBO conditions (1.083; SD: 1.618; p=0.717). Taken together, the questionnaire results show that our manipulation of ownership and agency in the BCI worked as expected. There was indeed a clear dissociation between agency, which was preserved in both conditions, and ownership, which instead was present only when the hands are in a first person perspective (see Fig.6)

We then compared the best mean accuracy across the four participants in the body ownership and non-body ownership conditions through a paired t-test. At the moment, we did not find any significant difference between the body ownership and no-body ownership condition, t(3)=0.498; p = 0.653;dz = 0.249 (Fig.7). This result is confirmed also by a Bayesian paired sample t-test, showing a Bayes factor of 2.114 in favor of the null hypothesis of no difference between the two conditions (BF01=2.114). However, it is important to note that our study is underpowered given the extremely small sample size. In this regard, a power analysis for sample size estimation indicated a critical sample size of 34 participants, specifying a medium effect size (dz) of 0.5 and a power of 0.80.

IV. DISCUSSION

We presented a pilot study aimed to investigate if agency felt over one’s own body differs in its EEG features from agency felt over an external device, without ownership. To this aim, we used a BCI paradigm where participants try to control two virtual arms presented in a first-person perspective or in a rotated position. If agency with body ownership, i.e., when the arms were controlled in a first-person perspective, differs from agency without ownership when the arms are rotated, then the decoding algorithm should be more accurate in one of these conditions. Crucially, in our pilot experiment we did not find any significant difference between the two conditions both in terms of algorithm accuracy and in the perceived agency. In contrast, the two conditions strongly differ in terms of body ownership felt over the virtual arms. Certainly these data should be taken with caution, given the very small sample size. However, if confirmed in the remaining participants to be tested (n=34), this result will indicate that the sense of ownership felt over a virtual device does not affect our accuracy in controlling its movements. Therefore, the absence of body ownership seems to be not detrimental for motor control’s accuracy. This is probably because the ”forward model” estimating the sensory outcomes of an action, predicts similar sensory consequences for actions involving tools or robotic devices[15],[16]. Thus, it is possible to assume that the forward model takes into account in its predictions not the body part per se, but rather the current effector, i.e., in our case, the two virtual arms. Another important aspect of our pilot results is that the absence of bodily movements is not detrimental for the sense of agency. This is in line with a recent study [11] showing that even when participants learn to control a robotic arm through a BCI, they still retain a sense of agency in absence of sensorimotor feedback. However, in this study the robotic arm was always presented in a first person perspective and authors did not control for possible effects of body ownership on the perceived agency. Thus, our study might truly demonstrate that exists a ”disembodied agency” [11] even in absence of body ownership over the controlled avatar. Most importantly, even the objective accuracy of our motor control seems to be not affected by the presence of body ownership. Thus, the sense of agency and motor control's accuracy can bypass both the sense of body ownership and an actual body movement. If these data are confirmed, we could state that a conjunction of two conditions may be sufficient for an accurate motor control and for the consequent sense of agency. First, an internal volitional signal to provide an experience of intentional action. Second, some external outcome consequentially to the internal volitional signal. Our data seem to suggest that the volitional signal need not have a hardwired connection to the external outcome to retain an accurate motor control. In our experiment, it was sufficient that the volitional signal and the external outcome had been associated.

It is important to highlight some significant limitations of our paradigm. First, the sense of agency is not a unitary phenomenon and we focused only on the explicit declaration that the external outcome was caused by one's own motor intention. We do not have an implicit and sensorimotor measure of the sense of agency, such as "the intentional binding, i.e., a perceived compression of an interval between voluntary actions and their sensory consequences. Second, we did not analyze how the accuracy changed during time in the two conditions. Based on what we argued, it is possible that in the ownership condition it is easier to associate one's own motor intention with the external output, as compared to the NBO condition in which the association between motor volition and outcome is less intuitive. Thus, we could hypothesize that the accuracy in the two conditions might differ in the first trials where participants are still learning the association. This difference will probably tend to disappear as soon as the association is fully learned. This is an intriguing hypothesis that we can put to test when data collection will be finished. Finally, it is possible to argue that the non-ownership condition is cognitively more difficult than the ownership condition because it requires also to perform a spatial rotation. Possible differences in accuracy between these two conditions should take into account the task difficulty. One possible solution could be to implement a second experiment in which the ownership felt over the virtual arms is manipulated with a training performed before the actual motor imagery task.

V. Conclusion

We investigated the role of body ownership and the sense of agency in controlling a virtual device. Participants use an EEG-based BCI to control two virtual arms presented either in a first person perspective to induce both a sense of ownership and agency over the virtual arms, or in a anatomical incongruent position to retain only the sense of agency. Preliminary data (n=4 participants) indicate that there is no difference between the two conditions in the EEG decoding algorithm reflecting the motor intention of the user. Crucially both conditions elicit a sense of agency over the virtual arms, although the sense of ownership was present only in the first person perspective condition. If confirmed in the remaining participants to be tested (n=34), these results will indicate that the ability of controlling an external device and the consequent sense of agency are not influenced by the sense of ownership felt over the device.

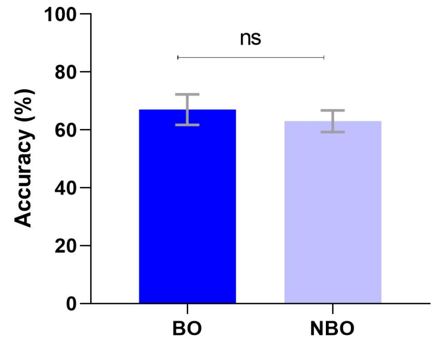

Fig. 7. The graph shows the average of the best accuracy as a function of the BO and NBO conditions. Error bars indicate standard error of mean.

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