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WHICH IMAGINED SENSATIONS MOSTLY IMPACT ELECTROPHYSIOLOGICAL ACTIVITY?

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ABSTRACT: Motor imagery brain-computer interfaces (MI-BCI) user training aims at teaching people to control their sensorimotor cortex activity using feedback on the latter, often acquired using electroencephalography (EEG). During training, people are mostly asked to focus their imagery on the sensations associated with a movement, though very little is known on the sensations that mostly favor sensorimotor cortex activity. Our goal was to assess the influence of imagining different sensations on EEG data. Thirty participants performed MI tasks involving the following sensations: (i) interoceptive, arising from the muscles, tendons, and joints, (ii) exteroceptive, arising from the skin, such as thermal sensations, or (iii) both interoceptive and exteroceptive. The results indicate that imagining exteroceptive sensations generates a greater neurophysiological response than imagining interoceptive sensations or both. Imagining external sensations should thus not be neglected in the instructions provided during MI-BCI user training. Our results also confirm the negative influence of mental workload and use of visual imagery on the resulting neurophysiological activity.

INTRODUCTION

Controlling one's own brain activity when receiving direct information regarding the former is a skill that can be acquired using neurofeedback training. During such training, people's brain activity is acquired, often using electroencephalography (EEG), and converted into a feedback that people have to learn to control [1]. The ability to modulate one's own brain activity can be used for two main types of applications. First, to use brain-computer interfaces (BCIs), that enable the control of external digital systems by producing discriminatory and stable brain patterns each associated with a specific command for the system [1, 2]. For instance, BCIs can be used to control the direction of a character in a video game or the direction of a wheelchair by imagining right or left-hand movements [3, 4]. Second, for neurofeedback (NF) applications for which the end goal is that the modifications occurring in the brain activity lead to cognitive improvements, often in clinical applications [5]. For instance, neurofeedback can be used for motor rehabilitation after a stroke [6].

Many of these applications are based on the users' ability to control their sensorimotor brain activity. To do so, people are often asked to perform motor imagery (MI) tasks, such as imagining hand movements. Indeed, observing, executing, or imagining sensorimotor tasks induces a similar desynchronization over the sensorimotor cortex [7–9]. Two main non-exclusive MI methods are discussed in the literature [8, 9]. The first one is visual motor imagery (VMI) when people imagine the visual characteristics of the movement, which notably involves the visual cortical network. The second one is kinesthetic motor imagery (KMI), when people imagine the somatosensations associated with the movement. Those somatosensations include both (i) exteroceptive sensations, i.e., all the sensations arising from the skin, such as thermal, touch, or vibration sensations, and (ii) interoceptive sensations, i.e., all the information arising from the muscles, tendons, and joints, such as muscle contraction but also higher-level information such as knowing where our limbs are located in space. We recommend the review from Hillier et al. on the history of the terms related to proprioception and the assessment of proprioception [10].

When training to perform motor imagery, the learners are most frequently instructed to perform KMI [1]. As stated in the first paragraph, most researchers use EEG to acquire brain activity, most likely because it is a portable and relatively cheap method of acquisition. In the rest of the article, we will mostly focus on the results obtained using EEG and specify if the results were obtained using another acquisition method. The use of KMI instructions is mostly justified by the results obtained by Neuper et al. in 2005 [8]. Among others, they investigated the neurophysiological activation resulting from KMI and VMI. They found that classification performances of the data acquired when people were doing KMI were significantly higher than the ones obtained based on the data acquired when they were performing VMI. The highest classification accuracy was reached over the left central electrode site (i.e., electrode C3, which is coherent with the task performed by the participants to imagine right-

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hand movements) with 67% of good classification with kinesthetic imagery and 56% with visual imagery. These results are in line with the results found by [11]. Conversely, recent results using EEG measures of connectivity found a better classification accuracy of VMI compared to KMI [9]. The type of imagery to perform could also depend on the task that needs to be learned and the stage of learning [12]. For instance, visual imagery seems more appropriate to learn the technical motor skill of drawing complex forms, while kinesthetic imagery enabled better temporal representation of the task [13].

The results on the influence of the modalities of feedback on BCI/NF efficiency could also provide insights regarding the sensations that should be associated with the motor imagery tasks. As such, the advantage provided by KMI compared with VMI is consistent with the results indicating that tactile and proprioceptive feedback (e.g., provided with vibrotactile actuators and orthosis) is more efficient than visual feedback in terms of classification performance, neurophysiological modifications, and user preferences [14].

As presented above, KMI involves many different sensations, among which the participants are left to choose from. For instance, the participants can decide to focus their imagination on the sensations arising from their muscles, and/or from their skin. Imagining exteroceptive sensations (i.e., sensation of pressure arising from squeezing a ball) in addition to interoceptive ones could significantly improve the classification performances based on EEG [15] or fNIRS [16] data, in particular, the ones of participants with poor performances (participants with performances below 70% for a BCI with 2 classes) [15]. Imagining the exteroceptive sensations associated with a movement could activate sensorimotor cortical structures and thereby improve BCI/NF user training [16]. Imagining exteroceptive sensations, i.e., vibrations on the back of the hand, does elicit desynchronization in alpha and beta bands (8-26 Hz), particularly in the upper alpha band and lower beta band (10-16Hz), over the sensorimotor cortex, i.e., C3 and C4 electrodes [17, 18].

Very little is currently known about the MI instructions that should be provided during BCI/NF user training, most of all regarding the potential influence of different external sensations. Our experiment therefore aims to study the influence of different somatosensory imagery tasks on neurophysiological activity with the aim of better advising our participants on the tasks they must imagine during MI user training.

MATERIALS AND METHODS

The neurotypical participants included in this experiment took part in a 2-hour long session where they had to imagine five types of somatosensations, corresponding to the different conditions. A within-participant comparison of the mental tasks was chosen. The order of presentation of the conditions was randomized across participants.

Participants: Thirty right-handed participants with good or corrected vision took part in this experiment (7 women and 23 men; age 21-60, M = 29.4, SD = 9.4). None of them had any history of neurological or psychiatric disorder. The study was conducted following the relevant guidelines for ethical research according to the Declaration of Helsinki. Participants gave written informed consent before participating in the study. The study has been reviewed and approved by Inria's ethical committee, the COERLE (approval number: 2023-30).

Experimental protocol: The experiment lasted about two hours during which the participants were seated in a comfortable armchair, in front of a monitor. The participants first answered two questionnaires notably assessing demographic information, e.g., age and handedness. The EEG headset was then placed on their heads and a video presenting the experimental instructions was presented to them. EEG data was then acquired for 2 minutes while the participants were asked to focus on the visual scenery of their choice. The maximum force that participants were capable of exerting was then measured using a dynamometer placed inside a foam ball that the participants had to squeeze as strongly as they could for 30 seconds. This measure was used to provide instructions calibrated to the maximal force of the participants during the experiment. Following that, the main phase of the experiment began. It was composed of 5 different conditions during which the participants imagined sensorimotor imagery tasks varying according to the type of imagined somatosensation, i.e., interoceptive, exteroceptive, or both, and the number of exteroceptive sensations, i.e., pressure only or pressure and vibration. For each condition, participants watched a video presenting specific instructions for the movements and sensations to imagine. They also performed and experienced the movement and sensations associated with the conditions (see Figure 1):

- **Interoceptive sensation (I)** – Hand grasping with force on an invisible object, i.e., without fully closing the hand to avoid exteroceptive stimulation.
- **Exteroceptive sensation of pressure (E1)** – Ball pressed on the inside of the hand without voluntary movements of the hand.
- **Exteroceptive sensation of pressure and vibration (E2)** – Vibrating ball pressed on the inside of the hand without voluntary movements of the hand.
- **Interoceptive sensation and exteroceptive sensation of pressure (IE1)** – Hand movement to squeeze a ball.
- **Interoceptive sensation and exteroceptive sensation of pressure and vibration (IE2)** – Hand movement to squeeze a vibrating ball.

The pressure exerted voluntarily, or involuntarily by the experimenter, on the participants' hand was controlled at 20% of the maximum force produced by the participant. Indeed, previous results found that imagining movement

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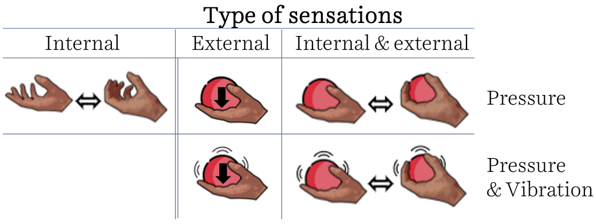

Figure 1: Experimental conditions: Interoceptive (I), Exteroceptive with pressure (E1), Exteroceptive with pressure & vibration (E2), Interoceptive & Exteroceptive with pressure (IE1), Interoceptive & Exteroceptive with pressure & vibration (IE2).

with different amount of force impacted the resulting brain activity [15]. Participants then had to imagine these different tasks during 20 trials each lasting 10 seconds. Runs lasted 4 min 30 seconds each. A break was offered to the participants between runs. At the end of these runs and for each condition, participants completed a questionnaire assessing their user experience. The questionnaire was composed of (i) the questions from the NASA-TLX [19] to assess mental workload and (ii) two questions based on the kinesthetic and visual imagery questionnaire (KVIQ) [20] to assess how clear the motor imagery task was in terms of visual and somatosensory representation with scales ranging from "No image" to "Image as clear as a movie" and from "No sensations" to "Sensations as intense as when performing the movement/feeling the sensations". All the questions were answered using an analogical scale ranging from 0 to 20. Finally, the EEG headset was removed and the participants completed the final questionnaire that evaluated which imagery task they preferred and which seemed the most effective and simple to imagine. This experimental protocol was presented and discussed at the French national BCI conference in 2023 [21].

EEG Recordings & Signal Processing: The electroencephalographic (EEG) data was recorded using 20 active electrodes, using a g.USBAmp EEG amplifier (g.tec, Austria). The electrodes were placed on the scalp of the participant over the sensorimotor area (at locations FC5, FC3, FC1, FC2, FC4, FC6, C5, C3, C1, Cz, C2, C4, C6, CP5, CP3, CP1, CP2, CP4, CP6 and Pz in the 10-20 system). They were referenced to the left earlobe and grounded to AFz. The data was sampled at 512 Hz, and processed online using OpenViBE 3.4.0 [22].

EEG data was preprocessed with MNE-Python [23]. The signal was filtered using a zero-phase notch filter with a 50 Hz cut-off and a finite impulse response band-pass filter with cut-off frequencies of 1 and 49 Hz and then average-referenced. We extracted epochs from 1 second before MI instruction cue to 10 seconds after. Epochs with peak-to-peak amplitude greater than 100 μV were rejected. Participants with more than 50% of total epochs rejected were removed from the analysis. As a result, 3 participants were rejected from the analysis.

Variables: Among the neurophysiological characteristics, we investigated the event-related potentials (ERPs), corresponding to either a desynchronisation (i.e., ERD) or a synchronisation (i.e., ERS) in the brain activity of our participants while they performed the different sensorimotor imagery tasks. To assess the ERPs, we first computed time-frequency representation using Morlet wavelets. We resampled the data at 256 Hz, and used a Morlet wavelet transform to calculate the EEG signal power between 12 and 20 Hz.

To have an idea of the evolution of the ERPs throughout the different trials, the resulting data was averaged across participants and electrodes (CP3, C3, C4, and CP4) for each conditions. Previous experiments mostly focused on C3 and C4. However, somatosensory data is primarily processed in posterior areas leading to the inclusion of CP3 and CP4 in our analyses [24]. The data was then normalized relative to baseline (the first second before cue) using a log-ratio of power at each time point relative to the mean power of the baseline, that we call *Power Evolution over Trial* in this analysis :

$$Power\ Evolution\ over\ Trial = log(Task/\overline{Baseline}) \quad (1)$$

Then, *Power Evolution over Trial* was averaged across time, excluding the first two seconds and last second of the trial providing the *Average ERD/S value*.

Finally, to investigate the potential reasons for the difference between our conditions, we used the answers to post-conditions questionnaires, NASA-TLX and the adapted KVIQ, to observe their correlation with *Average ERD/S values*. There are 7 different variables calculated from the questionnaires: “Mental demand”, “Temporal demand”, “Performance”, “Workload” and “Frustration” for the NASA-TLX; “Visual imagery” and “Kinesthetic imagery” for the KVIQ. Each variable was evaluated on an analogical scale ranging from 0 to 20, with lower values indicating lower workload for the NASA-TLX variables, and less vivid or clear imagery for the KVIQ variables.

RESULTS

In the first step of our analysis, we assessed the potential influence of our different experimental conditions on the cortical activity over the sensorimotor cortex throughout our trials.

To assess this, we first plotted *Power Evolution over Trial*, i.e., the evolution of *ERD/S* over time in the beta band (12.5-20 Hz), for our 3 major conditions (I, E and IE), averaged across participants and across *“Nb ext. sensations”* for condition E and IE (see Figure 2). A 1-second sliding average window was used for readability. On average, it seems that all the participants managed to desynchronize their brain activity over the sensorimotor cortex for the E and IE conditions, albeit seeming stronger for the E conditions. For the I condition, the brain activity over the sensorimotor cortex seems to have desynchronized until the third second and then steadily synchronized until the end of the trial.

Then, we were interested in knowing if these observed differences were significant, to assess this we use *ERD/S*

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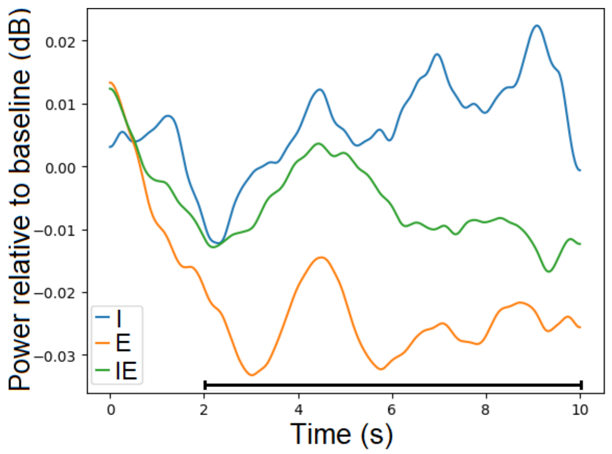

Figure 2: Average *Power Evolution over Trial* computed for each condition, with data smoothed using a 1-second window moving average. The black bar indicates the time window used for the analysis.

value. First, we used a Shapiro-Wilk test to verify the normality of *ERD/S values*. We found no significant deviation from normality ($W = 0.98$, $p = 0.66$) in our data. To avoid any distortion in the statistical results, we also checked the data for outliers. Any participant with an *ERD/S value* plus or minus two standard deviations relative to the median *ERD/S value* was considered an outlier and removed from our analyses. In total, 4 participants were removed from the following analyses.

We first studied the impact of the type and number of somatosensations imagined on the *Average ERD/S values*. As the interoceptive condition (I) was not associated with a number of exteroceptive sensations, it was first removed from the analysis. Thus, we assessed if the number of exteroceptive sensations, i.e., *"Nb ext. sensations"* (1 or 2) and the type of somatosensations, i.e., *"Type of sensations"*, (E or IE) had an impact on *Average ERD/S values* using a 2-way ANOVA with *"Type of sensations"* (E and IE) and *"Nb ext. sensations"* (Pressure and Pressure & Vibration) as independent variables. Our results indicate that ***"Type of sensations"* influences *Average ERD/S values*** [$F(1, 22) = 7.52$; $p = 0.01$; $\eta = 0.047$], but *"Nb ext. sensations"* [$F(1, 22) = 1.2$; $p = 0.208$; $\eta < 10^{-2}$] does not. A small trend could be present for *"MI type * Nb sensation"* [$F(1, 23) = 3.02$; $p = 0.1$; $\eta < 10^{-2}$].

To compare condition I to the others and since no significant influence of *"Nb ext. sensations"* was found on *Average ERD/S values*, we averaged E1 with E2 into E, and IE1 with IE2 into IE. We performed a one-way repeated measures ANOVA with *"Type of sensations"* (I, E and IE) as independent variable and *Average ERD/S values* as dependent variable. The results show **a significant influence of *"Type of sensations"*** [$F(2, 44) = 7.64$; $p < 10^{-2}$; $\eta = 0.13$]. To gain insight on this significant result, post-hoc analyses were performed and revealed a **significant difference between I and E ($p < 10^{-2}$), E and IE ($p = 0.02$)** but not between I and IE ($p = 0.27$).

Figure 3 reports the distribution of these values, showing a greater desynchronization for the condition E compared to both I and IE.

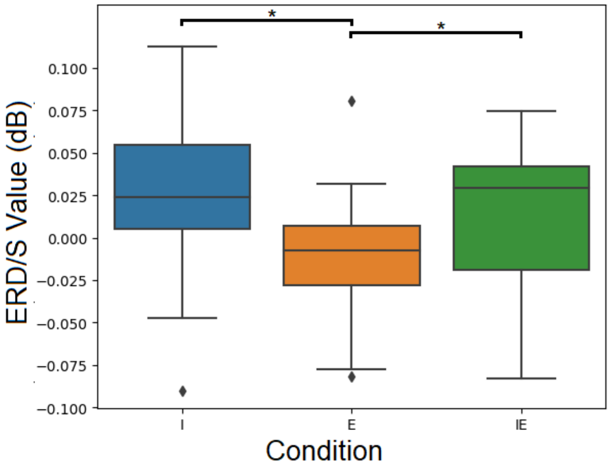

Figure 3: ERS/D recordings for conditions I, E and IE. Asterisks meanings: p<0.05: * ; p<0.01: ** ; p<0.001: ***.

Finally, to assess the potential causes of these significant differences, we studied the correlations between *Average ERD/S values* and the data acquired after each condition regarding the user experience. The correlations were assessed through Pearson correlation with False Discovery Rate (FDR) to correct for multiple comparisons. **A small significant positive correlations was found between *Average ERD/S values* and *Visual Imagery* ($r = 0.16$, $p < 10^{-3}$, *DoF* = 478) and between *Average ERD/S values* and *Mental workload* ($r = 0.12$, $p = 0.02$, *DoF* = 478)**. These correlations indicate that the more participants felt mentally overloaded, or felt that they performed realistic visual imagery, the less they produced strong ERDs.

DISCUSSION

In this study, the electrophysiological analysis focused on *Event-Related Desynchronization/Synchronization (ERD/S)* occurring over the sensorimotor cortex (i.e., C3/C4 and CP3/CP4) resulting from different sensorimotor imagery tasks performed by the participants. Visually, it seems that the participants managed to desynchronize their brain activity over their sensorimotor cortex in most conditions, except when imaging purely interoceptive sensation. This result might be related to the unfamiliarity of performing a hand-grasping gesture without any object in the center, as familiarity with a task was found to positively influence single-trial detectability of imagined movements [25]. There is a trend (p = 0.1) of interaction between the number of exteroceptive sensations and the type of somatosensations although further experiments should verify this interaction.

Our statistical analyses mostly revealed significantly stronger desynchronization when our participants imagined exteroceptive sensations compared to when they imagined (i) only interoceptive and (ii) both interoceptive and exteroceptive sensations. A distinct pattern of activation when imagining exteroceptive sensations is in line with the work of Yao et al. who worked on somatosensory imagery-based BCI and found relatively high average classification accuracy ranging from 77% to 85% depending on their studies [17, 18]. The classification performances obtained by Yao et al. using somatosensory imagery-based BCIs are similar to the ones obtained in motor imagery-based BCI with maybe a smaller number of persons who could not control the system compared to other studies. It should be noted that these results remain difficult to compare in terms of type of somatosensations imagined by the participants as they are left free to choose among different strategies [17, 18].

Based on previous work, we were expecting stronger ERDs when participants imagined both interoceptive and exteroceptive sensations compared to when they imagined interoceptive sensations alone [15, 16, 26]. This discrepancy could be the result of choices made in the design of our experimental paradigm. Indeed, when pressing the ball against participants' hands, the contact with the table added exteroceptive sensations at the back of the hand and could add a passive movement with small amplitude of the participant's hand producing interoceptive sensations. Thus, our exteroceptive sensations conditions (E1 and E2) were not purely composed of exteroceptive sensations and the amount of exteroceptive sensation was sensibly more important that in the two other conditions. This difference in exteroceptive sensations between E and IE did influence our results. We hypothesis that this increase in the amount of exteroceptive sensations could explain the discrepancy between our E and IE conditions but could also stress the importance of spatially distributed exteroceptive stimulation. Future experiment should consider adding symmetric external force to the back of the hand while the participants grasp the ball in both interoceptive and exteroceptive sensation conditions to counteract this bias. Additionally, we used the same ball for all participants regardless of their hand size leading to possible differences in the movement executed and imagined by participants. Following studies could use balls with different sizes to take into account the diversity of participants and keep the movement consistent across participants. Although, our analyses were comparing intra-participant data, so this factor should not have influenced our results.

Finally, we also discovered significant positive correlations between the ERDs and the workload experienced by participants. A negative influence of workload on BCI performance was already suspected as workload is one of the main factors influencing learning in general [27] and poor BCI performances were associated with high theta waves, which is an indicator of high workload [28]. Our results are in contradiction with the recent results from Gu et al. who found a positive influence of high workload on MI-BCI accuracy and desynchronization over the sensorimotor cortex [29]. However, the positive correlation between the ERDs and how realistically participants visually imagined the task is consistent with previous results from the literature [8, 11].

CONCLUSION

In this study, we designed and conducted an experiment studying the influence of sensorimotor imagery tasks to determine which sensations would elicit the largest desynchronization of the sensorimotor cortex. Our 30 participants performed five sensorimotor imagery tasks, each one with a different imagined somatosensation.

Results are consistent with the literature stating that we should encourage the participants to imagine exteroceptive sensations, such as pressure or vibrations, during BCI user training. We found significantly stronger desynchronization in the low beta band (12-20 Hz) over the sensorimotor cortex when our participants imagined exteroceptive sensations (either only pressure or both pressure and vibrations) compared to when they imagined only interoceptive sensations (from their muscles, tendons, and joints) and compared to when both interoceptive and exteroceptive sensations were imagined. Even though these results tend to indicate a limited role of interoceptive sensations imagery on resulting sensorimotor activity, our participants might still have imagined some interoceptive sensations while performing passive small movements. Higher level interoceptive sensations, such as the spatial perception of limbs in space, were also still present in the exteroceptive condition even though the exteroceptive tasks solicited them much less than the interoceptive condition. The differences in our conditions could also be explained by a greater surface of exteroceptive stimulation in the exteroceptive-only conditions. Future experiments with more complex experimental setup should further investigate this hypothesis.

In this article, we presented preliminary analyses of our results, the processing of our data is still ongoing. Future analyses will study more specifically the influence of our conditions on the temporal, spatial (notably between sensorimotor and motor cortex and lateralization), and frequency bands characteristics of our EEG data. Classification accuracy performances should also be computed to better compare our results to the ones reported in previous articles. Additionally, potential differences in user experience among our conditions will be investigated to gain insights on potential underlying factors explaining the differences observed in this article, especially the cognitive workload or the use of visual imagery.

Also, our results were obtained offline as our participants performed the tasks without any feedback on their brain activity. Thus, our results are not entirely comparable with previous ones that provided feedback to the participants regarding their brain activity. Future experiments should investigate how providing different sensorimotor imagery instructions influences participants' ability to learn to control their brain activity in BCI user training.

To build on theses first results, future analysis will focus on more frequency bands such as alpha/mu rhythms, and attempt single trial classification to determine which sensation are easier to discriminate from each other.

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