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Review of Jimmy PETIT's thesis dissertation

The thesis aims at creating an active and reactive BCI – BCI based on the response to a stimulus – that relies on tactile stimulation rather than on sight. The purpose of such BCI is to provide a novel way to interact with computers, which is meant for patients with severe motor impairments, including dysfunctional gaze control. Mental Imagery (MI) is used to specify the command rather than Attention Focusing (AF) on a specific part of the body. The author claims that the former allows to issue more commands than the latter.
The manuscript is generally very well written. It is clear and well organized. The scientific issues are addressed with great care and methodological rigor. The author should also be commended for tackling a highly complex challenge involving neuroscientific expertise, signal processing and clinical issues.

The first chapter lays down the goal and rationale for the study. It describes several challenges related to BCI, such as inter and intra-individual variability and data contaminations. It then presents the chosen approach based on SSSEP (Steady-State Somatosensory Evoked Potential) and MI. It ends with a simple and clear overview of the following chapters. This overview allows the reader to easily understand the logical link between the various studies presented throughout the manuscript. Figure 1.1, which is recalled all through the manuscript, is especially well thought of as it provides a nice illustration of the whole work.

The second chapter (published work) presents a literature review on SSSEP based BCI. This review was systematic and followed a very high-quality methodology that complied with PRISMA guidelines.

It started with a very clear and didactic description of the neural mechanisms that give rise to SSSEP, including a clear explanation of what the FOS (Frequency of Stimulation) stands for. It sounded like reading a textbook and could be a reference for the field. The following described the various techniques used to tune the BCI system to find the optimal FOS and then to process the EEG signal (frequency retrieval, spatial localization) and issue a command (selective sensation, attention focusing, mental imagery). The review was exhaustive and well conducted. Unfortunately, it ends with no real clear-cut conclusion about the accuracy that could be expected from SSSEP based BCI. Authors are not to be blamed for this, rather the paucity of studies seems to preclude any attempt to evaluate accuracy using meta-analytical procedures.

The third chapter (submitted work) is a theoretical contribution to signal analysis. It first lays out a mathematical model of EEG sampled data and derives a formula for the signal to noise ratio. It then presents three different signal processing techniques, namely, lock-in amplifier (LiA), canonical correlation analysis (CCA) and partial least squares (PLS). Thereafter, it uses the previously presented mathematical model of EEG data to compare those techniques. Finally, empirical EEG data from 2 participants are used to compare those techniques. The protocol used to collect the EEG data relied on an AF approach. Results based on synthetic as well as real data show that the CCA and PLS techniques are not suitable. Empirical results support the use of the LiA technique with a Laplacian filter (method called Current Source Density).

The fourth chapter (submitted work) reports a study on the use of MI to trigger commands on a SSSEP based BCI. It was meant to investigate a gating mechanism, that is, the modulation of the SSSEP due to filtering of redundant or irrelevant signals, in this case, mental motor simulation. The goal was to evaluate whether imagining the movement of a single wrist selectively modulated the associated SSSEP. Ten participants were included. SSSEP were correctly detected for 7 participants. Authors tested two methods to select FOS for the left and right wrists and the NC (non-condition) method seemed the most appropriate. The results of the experiment comparing MI of either the left wrist, right wrist or both wrist movements were not conclusive. Measured modulation of the SSSEP were not sensitive to the differences in MI, suggesting that the gating effect did not allow to selectively dissociate the imagined movement. Authors suggest that more training in MI would be needed. This could yet be discussed further as I will explain later on.

The fifth chapter (unsubmitted work) presents several different attempts to process the data acquired during the SSSEP based BCI sessions described in chapter 4. Firstly, the procedure used in the experiment described in chapter 4 to provide feedback to users is briefly summarized. The outcome was not conclusive. Second, the author presents offline classification procedures based on 4-classes and then 2-classes classifiers. The outcome was unconvincing as results showed that accuracy was lower than chance.

The sixth chapter (published work) investigates user experience in two BCI controlled applications. The first application was a kart driving game and the second was a puzzle-solving type of game. The two games were controlled with 4 possible commands: turn left, turn right, move forward, do nothing. Ten participants were included. As the designed BCI was not accurate enough, sham feedback was used to analyze different levels of accuracy. Data collection was carried out by asking users to fill in questionnaires about usability, workload, awakeness, tiredness, mood and emotion. Awakeness, mood and emotion staid steady while tiredness increased. Experienced performance, frustration and usability varied with the accuracy of the sham feedback. Several participants reported that it was hard to concentrate at the same time on the applications' task and MI to issue commands.

The seventh chapter discusses the results and concludes the thesis manuscript. This section is mostly a repetition of what has already been written. It does also add information about the planned future work. When summarizing the goals and purpose of the study, the author writes: "we investigated the possibility of SSSEP-based BCI providing four commands using only two stimulations by exploiting MI." Yet, the study (chapter 4) described in the manuscript only allows for 3 commands: MI for the left arm movement, MI for right arm movement, MI for both arms' movements. There is a fourth condition associated with no MI, but this does not really equate with a command. The author needs to be more specific about what the fourth command stands for.

The manuscript being based on articles, some of which have been accepted, the formatting, structure and English writing have already been thoroughly reviewed and revised. I therefore have little to say on those aspects that are overall of very high quality. I quite appreciated to be able to concentrate on purely scientific aspects and the following comments are mostly of this nature.

First, I have two points to raise regarding the rational for using MI over attention focusing (AF). The author claims that more commands can be issued with MI than with AF as the user can "imagine performing MI with one or more limbs simultaneously" (p. 4). This claim motivates the whole work and the core challenge of using MI in conjunction with SSSEP. However:
1) What is the difference between using 1 or 2 limbs in MI and focusing attention on 1 or 2 limbs? Authors claim it is easier to imagine moving 2 wrists simultaneously than to focus attention on the two wrists at the same time. Yet this claim needs to be substantiated. Future work mentioned in chapter 7 should perhaps address this question.
2) How do we know that the modulating effect on SSSEP during MI does not also involve some form of focused attention on the relevant limbs?

Another point that has been left out is the issue of the experience felt by users when using SSSEP in conjunction with MI. What does it mean on the cognitive level that MI modulates the amplitude of SSSEP? It seems to translate into increased cognitive workload according to users' interviews. Can it be seen as an interference between two cognitive processes?

I did not find the premise that SSSEP modulation is caused by a gating process entirely convincing. Gating, as I understand it, refers to a mechanism similar to sensory attenuation that filters out irrelevant stimulations. As suggested in the manuscript, in an embodied cognition framework, MI stimulation could be thought of as yielding incoming re-afferent signals – similar to self-inflicted stimulation but more implicit – and those signals could be considered as not needing further processing given that they are expected. Yet, this does not mean that signals caused by the vibro-tactile devices become more redundant or superfluous than before. The forward models (in the sense of Wolpert et al. (1995)) responsible for predicting the somatosensory consequences of action (here imagined action) should be specific enough to discriminate them from the incoming vibrotactile stimulations caused by an external device. How MI can influence SSSEP through a gating process is therefore not entirely clear to me as the sensory stimulation simulated with MI is quite different from the vibrotactile stimulus.

In addition, how AF and MI compare is unclear. From the way the experimental protocol in chapter 3 is designed to collect real data, it appears that AF is assumed to yield an increase in amplitude of the

SSSEP. By contrast MI, through the gating effect, is assumed to decrease the amplitude of the SSSEP. The direction of the modulation of the SSSEP signal thus seems to depend on whether AF or MI is used. One may wonder whether MI induces a gating effect or rather an attentional disengagement effect that would have the opposite influence on SSSEP compared to AF.

To conclude, I believe the thesis meets the required standards to be defended and I look forward to Jimmy Petit's presentation.

Reference:

Wolpert, D. M., Ghahramani, Z., & Jordan, M. I. (1995). An internal model for sensorimotor integration. *Science (New York, N.Y.)*, *269*(5232), 1880-1882.

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