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Beyond single user BCI

As a social species, we exist through the interaction with others and the external world. As we follow, lead and empathize with others, our perspective grows to embed the possible reaction of our peers [1]. This action-perception loop is dynamic and cannot be reduced to a single individual. Recently in neuroscience, it has been proposed to study the social interactions in the analysis of the *two-in-one-system*, the *hyperbrain* [2]. This field of study, known in neuroimaging as *Hyperscanning*, goes beyond the analysis of an isolated individual's brain activity and has already demonstrated that inter-brain synchronizations can be associated to several types of social behavior. [3]

On the other hand, with the growing attention on multi-user BCI systems [4], simultaneous brain activity recordings of people engaged in social interaction will be more and more common. However it can be troublesome to control the confounding factors of synchronizations generated both exogenously (sensory stimulation due to the game and BCI system) and endogenously (social interactions). To do so, we propose to begin with the well studied ERP-based BCI system. We developed a videogame with four social paradigms, namely, Solo (SO), Collaboration (CL), Cooperation (CO), Competition (CM) in conjunction with a Plug'n'Play state-of-the-art BCI chain.

Features

Accurate oddball paradigm

- Unpredictable flashing pattern with pseudo-random generated Inter-Stimulus Interval (ISI)
- Tunable parameters (ISI, pause, number of repetitions, number of symbols, bitrate, ...)

- adaptation of the difficulty according to the player performance (auto increasing/decreasing mean ISI)
- hardware tagging to minimize the jitter
- State-of-the-art methods**
- Online adaptive classification using Riemannian geometry
- no calibration required (Plug'N'Play) !

Open-source

- Signal acquisition and classification with OpenVIBE [5] (quick classification methods prototyping)
- GUI interface in OGRE (quick experimental protocol design)

Adaptive Online Classification

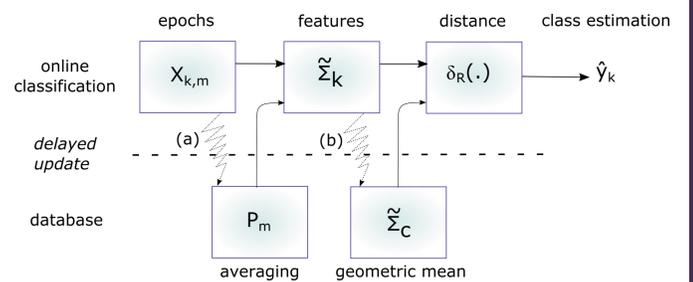


Fig. 6 : Online classification and adaptation pipeline

(1) Online classification

- For each subject m , extract each trial $X_{k,m} \in \mathbb{R}^{N \times T}$. The signal is BP filtered 1-20Hz, down-sampled to 128Hz. With $T=128$, $N=16$ (Fp1-Fp2-F5-AFz-F6-T7-Cz-T8-P7-P3-Pz-P4-P8-O1-Oz-O2)
- Build a "super-trial" by vertical stacking of P_m and $X_{k,m}$
- Compute the *super Sample Covariance Matrix* (SCM) of $\tilde{X}_{k,m}$ embedding the intra-subject's spatio-temporal statistics such as:
- In the case of 2 players in Collaboration, we extend this SCM to include the inter-subject statistics [6, 7] such as (Fig. 3):
- We classify each super SCM with the **Minimum Distance to Mean covariance matrices classifier (MDM)** using the Riemannian Framework (Fig. 7) [9]. The estimated class \hat{y}_k is given by finding the closest geometric mean according to the **Fisher information distance** δ_R such as

$$\hat{y}_k = \underset{C}{\operatorname{argmin}} (\delta_R(\tilde{\Sigma}_C, \tilde{\Sigma}_k)) \quad , C \in \{K^+, K^-\}$$

(2) Update of the database

Initialization on a representative database of the **ensemble average** ERP response and the geometric mean covariance matrix for each class TARGET (K^+) and NON-TARGET (K^-).

$$P_m = \frac{1}{|K^+|} \sum_{k \in K^+} X_{k,m}$$

At the end of each level:

- (a) P_m is updated
- (b) The geometric mean covariance matrix $\tilde{\Sigma}_{K^+}$ and $\tilde{\Sigma}_{K^-}$, for class K^+ and K^- respectively are updated using a geodesic interpolation. This step allows the classifier to be used in an **adaptive way without training session** [6,7,9]. A forgetting factor (step in the geodesic) can be tuned online to adapt the speed of the learning.

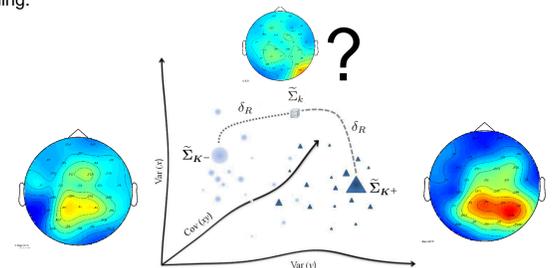


Fig. 7 : The Riemannian distance between the current trial and the geometric mean $\tilde{\Sigma}_C$ is the shortest distance (geodesic) in the manifold of Symmetric Positive Definite (SPD) matrices [10].

Adapting The Social Paradigms

- **Solo:** each player's performance is completely independent from the performance of the other player and from social factors.
- **Collaboration:** several subjects have the same task and the same stimuli.
- **Cooperation:** several subjects work together with a mutual goal but they obtain individual rewards according to their own performance that is modulated by the group performance
- **Competition:** several subjects have the same goal but the player with the best performance will have a greater reward.



Fig. 2 Two participants playing during the experiment bi2015b

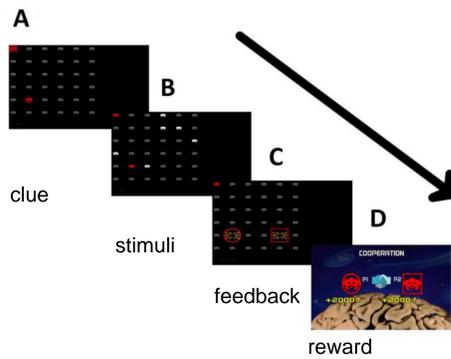
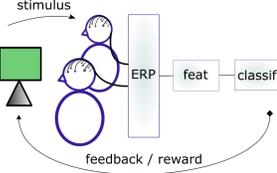


Fig. 1 : Brain Invaders v2 sequence. (A) Level initialization. (B) After a short delay, the game flashes randomly all the symbols twice. (C) The game destroys the most likely alien(s) according to the classification. (D) If the player(s) succeed(s) at destroying the target(s), s/he (they) is awarded by a fixed amount of points or by a factor proportional to the number of repetitions required.

Solo/Collaboration



Cooperation/Competition

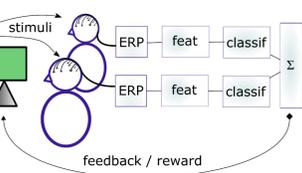


Fig. 3 The game proposes different classification strategy depending of the social paradigm. In CO/CM the players can have different stimuli/tasks.

Results

Online classification

- the performance is **reliable** in different hardware conditions (wet, dry electrodes).
- the game has been described by the participants as **engaging and entertaining**.

Inter-Brain Synchrony

While the participants performances are not significantly different between Cooperation and Competition (Fig. 4), we observe a difference in inter-brain PLV_n [11] (see Fig. 5) in Delta (1-3Hz) waves between [0,375, 0,4375]s in centro-parietal location.

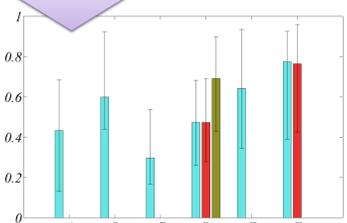


Fig. 4 : Median, 0,1 and 0,9 quantile of the ratio of successful classification during the online experiments. Details are presented in Table 1. When several performances are shown, it refers to the column "Mode(s)" in Table 1 (respectively in order).

Table 1 List of the experiments using the Brain Invaders software. Chance level is 1/36

| Database | Mode(s) | # subjects | # sessions | Electrodes | Min (%) | Av (%) | Max (%) | Ref. |
|----------|---------|------------|------------|------------|---------|--------|---------|------|
| A | bi2012a | 26 | 1 | 17-wet | 28.19 | 47.79 | 68.94 | |
| B | bi2013a | 24 | 1 | 16-wet | 42.86 | 62.88 | 92.31 | [6] |
| C | bi2014a | 71 | 3 | 16-dry | 16.67 | 35.55 | 72.97 | |
| D | bi2014b | 38 | 4 | 2x32-wet | 36.73 | 68.30 | 94.74 | [7] |
| E | bi2015a | 50 | 3 | 32 wet | 33.33 | 68.04 | 100 | |
| F | bi2015b | 44 | 4 | 2x32 wet | 27.5 | 74.0 | 98.75 | |

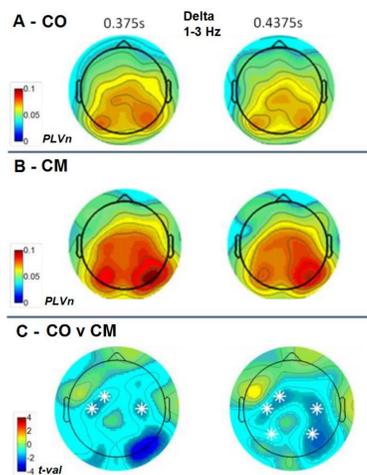


Fig. 5 : bi2015b. Inter-Brain Phase Locking Value (electrode to electrode) scalp distribution in cooperation (A) and competition (B). (C) shows the t-value map between the two conditions. Cluster-based permutation tests revealed a difference between CO and CM ($p < 0.05$) mainly in centro-parietal regions in the delta band.

Discussion

Brain Invaders - Future work

-**Smart initialization** of the ensemble average ERP and geometric mean. Fully **unsupervised** adaptive classification.

On inter-brain synchrony

-Cluster-based permutation test emphasizes a difference in Delta (1-3Hz) phase locking value

between CO and CM. This finding should be investigated further as sustained attention has been suggested to modulate Delta response in ERP [8]

-Inter-brain electrode-to-electrode PLV may miss inter-brain synchronizations as they can be spatially asymmetrical between subjects.

-Connectivity estimation using blind source separation approach is under investigation.

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