# Brain Signatures of Team Performance

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**Abstract.** We report results from a dual electroencephalography (EEG) study, in which two-member teams performed a simulated combat scenario. Our aim was to distinguish expert from novice teams by their brain dynamics. Our findings suggest that dimensionality increases in the joint brain dynamics of the team members is a signature of increased task demand, both objective, e.g. increased task difficulty, and subjective, e.g. lack of experience in performing the task. Furthermore in each team we identified a subspace of joint brain dynamics related to team coordination. Our approach identifies signatures specific to team coordination by introducing surrogate team data as a baseline for joint brain dynamics without team coordination. This revealed that team coordination affects the subspace itself in which the joint brain dynamics of the team members are evolving, but not its dimensionality. Our results confirm the possibility to identify signatures of team coordination from the team members' brain dynamics.

**Keywords:** team, coordination, manifold, dimension, brain, dynamics, subspace, EEG.

## 1 Introduction

Real-world tasks and military missions often require the coordinated efforts of many team members for successful completion. Success within a team format is

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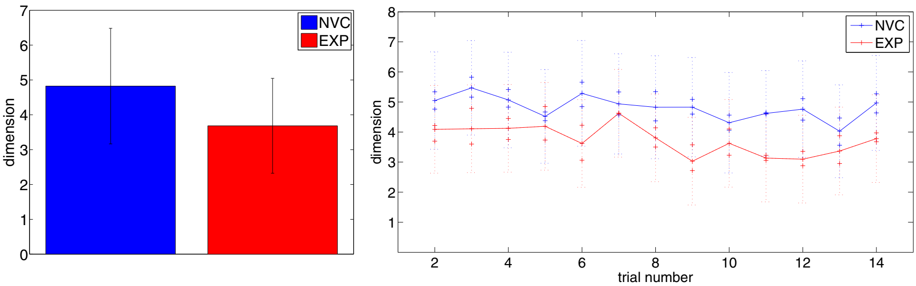
critically dependent on the ability of members of the team to work effectively together. A team whose members can work effectively together to accomplish team objectives may be considered as an expert team. Understanding how an expert team functions has been a topic of study in diverse fields, such as sports psychology and business management. The objective is simple: if we can understand how expertise develops within a team and the relevant variables that determine how an expert team operates, then training can be directed. Recently, Dodel et al. have developed a new approach for the study of team dynamics that avoids the need to understand team dynamics in detail and yet can still capture complex behaviors often expressed by expert teams [1]. This approach starts with the measurement of behaviors performed by members of a team. These behaviors evolve over time as the team advances towards the goal. The unfolding of behavior over the course of goal achievement defines a trajectory. If the same task is repeatedly performed and measured, multiple trajectories are defined and span a manifold which is shaped by constraints imposed by the task itself as well as by the interaction between the team members. Expert manifolds can be defined and used as the criterion standard for understanding novice manifolds, thus removing the need for a coach or teacher to evaluate team performers. In this study, we extend the concept of manifolds to the neural domain to help us further understand the complexity of expert team dynamics. We used dual electroencephalography (EEG) to simultaneously record the brain activity of the members of two expert teams and two novice teams, respectively. Each team consisted of two subjects which performed a test scenario in a simulated realistic and challenging combat situation. The scenario has been intentionally structured so that it necessitates extensive coordination and communication between the team members. Each trial comprises a time point ("turning point") after which simulated hostilities occur. The three specific goals of our analyzes were to (1) characterize differences between novice and expert teams based on the brain dynamics of the team members, (2) characterize differences in brain dynamics before and after the onset of simulated hostilities (3) find signatures of team coordination in the brain.

## 2 Results

### 2.1 Dimensionality of Brain Dynamics in Experts and Novices

One of our key hypotheses on team coordination states that coordinated team dynamics evolves along a particular manifold, the geometry of which reflects task related constraints as well as effects of team coordination. Such a manifold has been successfully constructed for behavioral team data and is hypothesized to exist for neural team data as well. There are multiple ways to define such a manifold. Here we computed the local subspaces of the joint brain dynamics of the team members to approximate the team manifold (see Materials and Methods). We found that the local subspaces changed rapidly over time, thereby reflecting the highly dynamic nature of the brain signals. As an approximation of the local dimensionality of the manifold, we first assessed the intrinsic dimensionality of the local subspaces in which the joint brain dynamics evolves using a sliding window of 320 ms (see Materials and Methods). Taking the average over the whole time interval of the trials, we found that novices had a higher mean intrinsic dimensionality of their joint brain dynamics than experts (Fig. 1(a)). This result was highly consistent over trials (Fig. 1(b)).




(a) (b)

**Fig. 1.** Dimensionality of the joint brain dynamics (sliding window length: 320 ms) of novices (blue) and experts (red). (a) Mean over time and trials. Error bars: standard deviation. (b) Mean over time for each trial averaged over both teams of the same team level, respectively. Dotted lines: standard deviation.

### 2.2 Brain Dynamics before and after Onset of Simulated Hostilities

One of our hypotheses was that the degree of team coordination will be different before and after the turning point (the onset of simulated hostilities) and that this difference will be stronger for the expert team than for the novice team. Comparing the time-averaged intrinsic dimensionality of the joint brain dynamics before and after the turning point, we found that there is a tendency towards higher dimensionality after the turning point, in particular for the experts (Fig. 2).

The overall effect is small and can be considered only as a trend, but the effect was highly consistent over trials as assessed by computing significance values from the binomial distribution. In the expert team the effect of dimensionality increase was highly consistent with a significance of $p < 0.001$. The effect was less consistent for the novice team ($p < 0.03$). In addition we assessed the effect also in the single subject data, where it was significantly consistent in both subjects of the expert team ($p < 0.001$ and $p < 0.011$, respectively), but only in subject 2 ($p < 0.005$) of the novice team. Furthermore in the experts the increase in mean dimensionality after the turning point occurred congruently in both joint and single subject brain dynamics for most of the trials. This was not the case in the novice team.

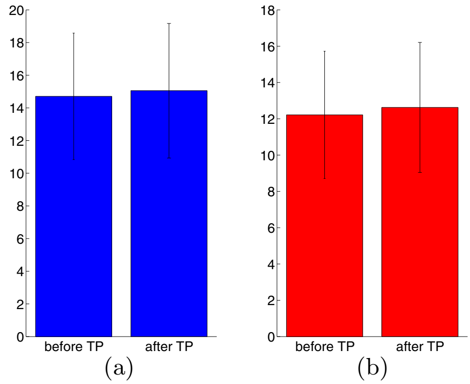



**Fig. 2.** Mean dimensionality of the joint brain dynamics before and after the turning point (TP), which marks the onset of simulated hostilities. Sliding window length: 10s. (a) novices (blue), (b) experts (red), error bars: standard deviation.

### 2.3 Manifold Spanned by the Joint Brain Dynamics of the Team

To get insight about the overall subspace in which the joint brain dynamics on the manifold evolves, we computed a team subspace from the local subspaces (see Materials and Methods). The team subspace for one expert team in a 20 s interval around the turning point is shown in Figure 3. Three of the four dominant spatial modes show localized activity over right prefrontal electrodes in one or both team members, indicating that joint activity in this area in both team members could play a role in team cognition. At each point in time the team subspace accounts for about 10-40% of the data as shown by the reconstruction quality of the data with respect to the subspace (Fig. 3(b)) with the highest reconstruction qualities occurring after the turning point.

### 2.4 Signatures of Team Coordination

So far we have analyzed signatures of team performance by approximating the hypothesized team manifold dynamically by identifying subspaces of the joint brain dynamics of the team members. Here we extend this approach to identify the aspect of coordination in a team. To determine signatures of team coordination we created surrogate teams with the same performance level as the original teams but without team coordination. This was achieved by pairing the data from two subjects of the same teams, but from different trials (e.g. data from trial 3 in subject 1 combined with data from trial 4 in subject 2). The surrogate data hence serves as a baseline to isolate effects of team coordination. When surrogate data are constructed the alignment of coordinating dynamic elements is lost and scrambled, which is equivalent to a loss of team coordination. As a consequence, the team manifold should change for the surrogate data set.

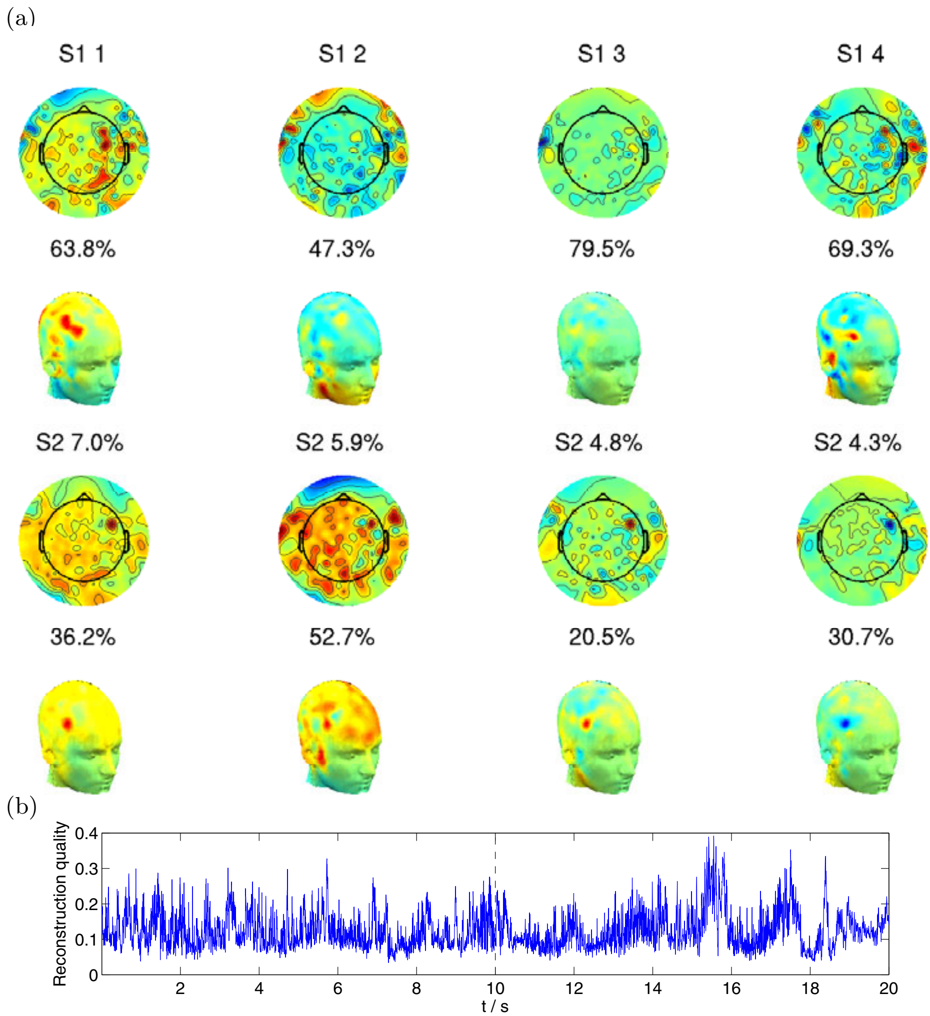



**Fig. 3.** Subspace in which the joint brain dynamics of the expert team evolves in an interval of 20 s around the turning point (dashed line). (a) Topographic maps and head plots of the first four spatial modes of the 16-dim. team subspace of expert team 1. For visualization purposes each subject has its own color map centered at zero (green). Percentages on top of the head plots: contribution of each subject to the total spatial mode. Percentages on top of the topographic maps of subject 2: contribution of the spatial mode to the total variance of the data in the team subspace. (b) Mean reconstruction quality of the expert team data with respect to the team subspace.

We first tested this hypothesis by comparing the dimensionality of the team subspaces of true and surrogate teams and second we computed the similarity of the two types of subspaces (see Materials and Methods). While we found that the dimensionality of the two types of subspaces was essentially the same, the team subspaces of the real teams differed from the team subspaces of the surrogate teams in about three dimensions. We could hence identify a three dimensional subspace of joint brain dynamics of the team members which is specifically related to team coordination. The dominant spatial modes of this subspace had similar features as the dominant spatial modes of the team subspace (cf. Fig. 3), in particular it also showed localized activity over right prefrontal electrodes in both team members.

## 3 Materials and Methods

### 3.1 Data Acquisition and Preprocessing

High density EEG data (256 channels) with a sampling rate of 250 Hz was acquired simultaneously from the two team members of four teams (two novice teams, two expert teams) in a simulated combat scenario where the subjects were coordinating to accomplish a common goal. Data from 14 trials were acquired from each team. Each trial lasted about 20 minutes and comprised a time point ("turning point") after which simulated hostilities occurred. We aligned all data sets with respect to the turning point and equalized the time intervals before and after the turning point, resulting in trial lengths of about 16 and 26 minutes for experts and novices, respectively. To account for transiently faulty electrodes, in every data set of each subject we discarded the 30 electrodes with the highest variances over time, still leaving almost 90% of the electrodes available for analysis. The data was cleaned from eye blink artifacts by an in-house program developed by EGI.

### 3.2 Team Manifold and Dimensionality

The measured brain dynamics of the teams evolve in a high-dimensional state space (here: $2 \times 256$ channels $= 512$ dimensions). A team manifold was approximated by computing subspaces of the joint brain dynamics of the two team members using a sliding window. For each window the subspace was computed by performing a singular value decomposition (SVD) of the joint data of subjects 1 and 2, created by concatenating the channel data of the two subjects at each point in time. Prior to concatenating the total spatio-temporal variance of the data of the two subjects was equalized to eliminate effects of inter-subject variability in signal strength. Dimensionality of the manifold was assessed by the dimensionality $d$ of the subspaces for each time window from the SVD of the data matrix according to

$$d = N + 1 - \sum_{i=1}^{N} \frac{\sum_{j=1}^{i} \sigma_j^2}{\sum_{l=1}^{N} \sigma_l^2} \quad (1)$$

where $N$ is the total number of singular values $\sigma_j$, $j \in \{1, \ldots, N\}$.

### 3.3 Team Subspace and Reconstruction Quality

The team subspace was determined by performing an SVD over the concatenation of the basis vectors of all subspaces of the joint brain dynamics of the team members, weighted by their singular values and using their respective dimensionality. Reconstruction quality $r(t)$ of the data with respect to the team subspace was assessed at each point in time $t$ by

$$r(t) = \frac{\|\mathbf{P}\mathbf{v}(t)\|^2}{\|\mathbf{v}(t)\|^2} \tag{2}$$

where $\mathbf{P}$ is the projection matrix onto the team subspace and $\mathbf{v}(t)$ is the joint data at time $t$. Furthermore $r(t) \in [0, 1]$ with 1 indicating perfect reconstruction.

### 3.4 Similarity of Team and Surrogate Subspace

We assessed the similarity between the team subspaces of the true team and the surrogate team by determining whether they had a common subspace. A common subspace can be determined by solving an eigenvalue problem as follows. Let $\mathbf{X}$ be an $m \times n$ matrix, $n \leq m$, the column vectors of which span the team subspace, and $\mathbf{Y}$ an $m \times k$ matrix, $k \leq m$, the column vectors of which span the surrogate subspace. The vectors in the common subspace may be written in both bases $\mathbf{X}$ and $\mathbf{Y}$ using an $n \times 1$ vector $\mathbf{a}$ and a $k \times 1$ vector $\mathbf{b}$ with the relation

$$\mathbf{X}\mathbf{a} = \mathbf{Y}\mathbf{b} \tag{3}$$

We can solve eq. (3) for $\mathbf{a}$ or $\mathbf{b}$ using the pseudo-inverses $\mathbf{X}^+ := (\mathbf{X}^T\mathbf{X})^{-1}\mathbf{X}^T$ and $\mathbf{Y}^+ := (\mathbf{Y}^T\mathbf{Y})^{-1}\mathbf{Y}^T$ of $\mathbf{X}$ and $\mathbf{Y}$, respectively. This yields

$$\mathbf{a} = \mathbf{X}^+\mathbf{Y}\mathbf{b} \tag{4}$$

$$\mathbf{b} = \mathbf{Y}^+\mathbf{X}\mathbf{a} \tag{5}$$

Inserting eq. (5) into eq. (4) yields

$$\mathbf{a} = \mathbf{M}\mathbf{a} \tag{6}$$

with the $n \times n$ matrix $\mathbf{M} := \mathbf{X}^+\mathbf{Y}\mathbf{Y}^+\mathbf{X}$. Eq. (6) is an eigenvalue problem which is solved by the eigenvectors to the eigenvalue 1 of the matrix $\mathbf{M}$. The multiplicity of the eigenvalue 1 equals the dimensionality of the common subspace, and the eigenvectors $\mathbf{a}$ can be used to obtain a basis of the common subspace in terms of the basis $\mathbf{X}$ of the team subspace. The subspace reflecting team coordination consists in the complement of the common subspace and can be constructed from the eigenvectors to the eigenvalues $\neq 1$ of $\mathbf{M}$.

## 4 Discussion

Behavioral signatures of coordination typically are based on the variability of measures that characterize behavioral dynamics. The underlying assumption is that coordination induces coupling between individuals and hence decreases the variability related to independent behavior. Typical examples include the variance of the relative phase (see [2] for a review) and variability across manifolds (Uncontrolled Manifold (UCM)) [3]. More recent approaches to characterize coordination include the description of behavioral processes [4–8] using mathematical representations of flows on manifolds in the state space of a given system. The beauty of this approach is its generality and its ability to account for complex behaviors which may be represented by curved manifolds in state space. Dodel et al. [1] applied this approach to team coordination. They reconstructed the flow on the manifold in the shared behavioral state space of all team members and demonstrated that this manifold may serve as a tool to compare different levels of team performance against a gold standard (the expert team performance). Here we have taken this effort one step further, and considered the existence of a shared brain state space in analogy to the behavioral state space of [1]. The brain state space is spanned by all electrodes of all team members. Our hypothesis was that, if team coordination is indeed reflected in neuroimaging data, a common manifold exists in the brain state space along which the joint brain dynamics of the team members evolves. Such manifolds have been recently postulated to dominate the resting state brain dynamics of individuals [9–12], and may reflect temporal or spatial modulation in the brain [13].

In the current study we have attempted to identify manifolds of brain dynamics which reflect processes of team performance and coordination in the members of a team. Our specific goals were to (1) characterize differences between novice and expert teams based on the brain dynamics of the team members, (2) characterize differences in brain dynamics before and after the onset of simulated hostilities (3) find signatures of team coordination in the brain. Our results indicate that novice and expert teams exhibit different characteristics in their brain dynamics as measured by dual EEG when performing a highly nontrivial ongoing task. In particular brain dynamics in expert teams were lower dimensional than in novice teams. Increased task demand was associated with a consistently higher dimensionality in the expert team, whereas this effect was less consistent in the novices.

Investigation of team cognition from behavioral measures has a long tradition [14–16]. More recently, there is also increasing interest in analyzing how interactions between humans are reflected in the individuals' brain activity [17–23]. Our approach is different from the latter approaches in that it allows identifying team coordination by directly comparing signatures of joint brain activity in team members with and without team coordination. This is achieved by producing surrogate data in which team coordination is selectively removed while retaining the performance level of the individual team members. The introduction of a surrogate team provides a baseline and could be used to develop significance measures. Ideally surrogate data should consist of trials with the exact same behavior of the subjects as in the original trial, but without team coordination. To a first approximation of this ideal we used data where the individual subject data was taken from different trials of the same task. Using surrogate data we identified a subspace which was related specifically to team coordination. The spatial modes spanning this subspace showed localized joint activity over the right prefrontal electrodes in both team members, which indicates that this area could play a role in team coordination.

Given the complex nature of brain imaging signals (spiking neuron networks generate oscillatory dynamics that is only partially picked up by non-invasive brain imaging), we did not pursue a detailed reconstruction of the shared manifold in brain state space, but nevertheless found some evidence of its existence. The phenomenological characterization of the manifold in terms of non-invasive brain imaging is not unique. Therefore the reconstruction of the manifold could be improved by using various derived properties of the data, such as separate frequency bands, instead of the raw data. Furthermore, here we have used only team level (novice or experts) and task demand (before and after onset of simulated hostilities) as task descriptors. More task descriptors such as communication status between the team members or information about situational content could be used to refine the analysis and identify brain activity patterns related to specific team situations.

## 5 Conclusion

This study shows proof of concept that even in a highly uncontrolled real-world task setting it is possible to identify signatures of team performance and team coordination from the brain dynamics of the team members. In particular, our results indicate that dimensionality increases in brain activity is a signature of increased task demand, both objective, e.g. increased task difficulty, and subjective, e.g. lack of experience in performing the task. An integral part of our approach is the identification of brain signatures of team coordination by means of surrogate team data. While our results do not support the use of dimensionality as a signature of team coordination, we were able to identify a subspace of brain dynamics which is related to team coordination. This is the first evidence that a manifold of team coordination may exist in the brain state space across all team members. If that is the case, the manifold is a prime candidate for a neural biomarker of team coordination.

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