# Behavioral and Brain Dynamics of Team Coordination Part I: Task Design

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**Abstract.** In this study, pairs of subjects performed a team-intensive task with the shared goal of clearing a virtual room from threats. Our goal was to identify signatures of efficient team work from a dynamic analysis of both subjects' brain signals and behavioral performance. An ecologically valid task of room clearing was designed and a novel analysis framework was developed to address the challenge of understanding complex, continuous social processes at both behavioral and brain levels. In the present paper, we detail the design of the task, and present validation techniques undertaken to acquire and analyze high-quality and accurately timed neurobehavioral information. A companion paper will discuss the neurobehavioral findings and their implications.

**Keywords:** Neuromarkers - EEG - neurobehavioral dynamics - social behavior - complexity.

## 1 Introduction

One of the most extreme forms of team coordination is observed when members' survival and safety depend upon efficient team interactions, such as when Marines neutralize dangers in a confined urban environment. During such tasks, like clearing a room in a hostile environment, a host of behavioral, cognitive and social processes have to be coordinated in space and in time in a context-dependent fashion. The right process at the wrong time may be deleterious to performance. The goal of this study was to create a framework to quantify the dynamics of neurobehavioral processes unfolding during such ecologically valid tasks that place a high demand on both individual and team coordination.

Our framework aims at quantifying inter-individual variability in team performance, team compatibility, and intra-individual skill learning characteristics of novices trained to perform team-intensive tasks. To combine neural and behavioral dynamics, we developed new tools aimed at revealing the link between brain and

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behavior in real time [1]. These tools are geared to circumvent a limitation of conventional neuroscientific studies in which only a handful of processes can be assessed at once and whose organization is typically determined by the experimenter.

The underlying tenet of our work is that identifying dynamical neuromarkers and linking them causally to truly complex behaviors that evolve adaptively over time adds critical information. For example, in other contexts such as recovering from head injury, it has been shown that even though behavioral indices have returned to normal, the underlying neural circuitry has certainly not [2]. Also, in typical studies performance error and deficiency are revealed only for a subset of environmental circumstances, whereas deficient neural processes are more frequent, and precede the onset of observable behavioral errors. We argue that a dynamic neurobehavioral framework is all the more important for high-level tasks such as team coordination, because of the complex and intricate architecture of the behavioral, cognitive and social processes that must be recruited for successful performance. In the following, we present some preliminary findings from a very rich data base as well as the methodological framework which is based on the concepts and principles of Coordination Dynamics [3].

## 2 Materials and Methods

### 2.1 Subjects

Nine pairs of subjects participated in the experiment (n=18, 1 female, 17 male) with an age range of 20 to 45 years (mean = 28.2). All subjects had normal or corrected to normal vision, and no motor dysfunction. All but one subject was free of psychoactive medication. The results from the medicated subject were not different from others and his data were included in the group analysis. Upon successful completion of the experiment, subjects received a $20 gift card. The protocol was approved by the Florida Atlantic University Internal Review Board and was in accordance with the Declaration of Helsinki. Informed consent was obtained from all subjects.

### 2.2 Behavioral Task

The task was designed to retain the essence of key behavioral, perceptual, cognitive, social and attentional processes that participate in successful team work (Figure 1A), and followed the main lines of an instructional video of room clearing by the VIRTE program at Clemson University. The processes were integrated into a videogame, in which participants shared the same top down perspective of their virtual environment (Figure 1C). The task was designed and run under XNA (Microsoft Co). Pairs of subjects sat at a table facing a computer screen while holding an Xbox controller (Nyko, China, see Figure 1B). They performed coordinated room clearing, stacking and cueing one another to entry, moving to and covering their areas of responsibility and deciding upon firing at occasionally present enemy (and sometimes friendly) avatars. Subjects controlled their avatar's position and direction of gaze, as they navigated through a series of 32 buildings each composed of 5 successive rooms, with their virtual environment becoming visible upon the avatars' spatial exploration.

Trials started with both avatars stacking along a closed door (Figure 1D-E). At a ready signal by the partner conveyed through touch 'tap' in the real situation and provided through a vibration of the Xbox controller; (verbal communication was not allowed due to EEG artifacts), the avatar closest to the door initiated motion, opened the door with the press of a button on the Xbox controller (Figure 1B) and chose as destination either the left or right corner adjacent to the door. The partner's task was to follow immediately and orient to the opposite corner. Subjects were instructed to follow one of two entry techniques. One entry pattern named "crossover" required the avatar to move diagonally to the opposite corner alongside the wall on which the door is located (movement path for the green avatar in Figure 1D, blue avatar in Figure 1E). The other entry pattern named "buttonhook" required performing a $180^{o}$ turn (blue avatar in Figure 1D, green avatar in Figure 1E). Given that the leader did not communicate to the follower the type of entry he/she was about to perform, the decision of the follower had to be based on perceptual information regarding the leader's entry pattern. After crossing the door threshold, subjects were asked to move the avatars uninterruptedly until they reached the corners of domination (corners 1 and 2 in Figure 1D-E).

Information about the room was not provided at once, but revealed itself as the avatars explored their environment. A "fog-of-war" was initially present, and avatars' cone of vision revealed the details of the room (walls, enemies and friendly inhabitants). While moving toward the corners of domination, subjects were instructed to initiate scanning of their environment--a behavior called pieing—aimed at optimizing exploratory gaze behavior. That is, they had to divert the cones of vision from their heading direction and rotate it toward the center of the room. This behavior speeds up the discovery of threats in the environment. Upon reaching the corners of domination, the avatars had to adopt a pattern called "interlocking sector of fire", in which their cones of vision was intersecting on the median position of the opposite wall.

Rooms were either empty or had a friend (circular shaped avatar displayed in magenta color) or enemy (orange color) located at pseudorandom spatial locations. The complete session included a total of 52 friends and 52 enemies. The task was designed such that there was never more than one inhabitant per room. When an inhabitant was discovered, subjects were required to make a shoot/no-shoot decision, while following instructions not to slow down their path through the room.

Each action sequence (clearing a building) was composed of 5 successive rooms, all of rectangular shape, with varying dimensions in order to maintain a level of uncertainty on the part of the avatars. After reaching the corners of domination and having secured the current room, avatars were moved to restack along the next door: the sequence of room clearing was then repeated until the entire building was cleared.

In a practice/familiarization session that took place one day preceding the experiment proper, subjects were instructed on correct room clearing techniques and practiced in the virtual environment for about an hour. Warm-up practice was repeated the day of the main experiment while subjects' scalps were prepared for EEG recording. To improve their learning of the task, following each behavioral sequence subjects were asked to provide self-rating on key performance variables such as proximity to the partner upon entry, absence of slowing down during entry, shooting and early pieing readiness. Ratings were provided on a scale from 1 to 10, with 10 being rated as a very good performance, and 1 as a poorly executed performance.

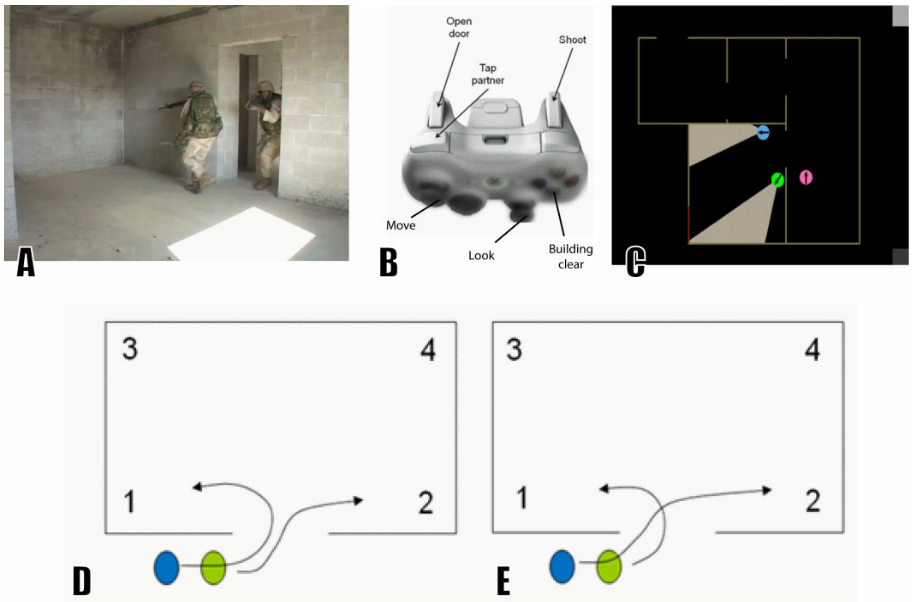


**Fig. 1.** (A) A live room clearing upon which the task is based (reproduced from Muth and Hoover). (B and C) show the Xbox controllers used in the experiment and a snapshot of the task respectively. (D-E) depicts the two entry patterns to corners of domination 1 and 2. Subjects identified their avatar as an isoluminant colored circle (blue and green). Leader performed either a crossover (D) or a buttonhook entry pattern (E), follower performed the complementary path.

### 2.3 Behavioral Recording

Behavioral data collection was handled by the computer running the room clear software. A log entry line was written at each graphical refresh for each avatar, which included position and direction of gaze, room location, and binary state variables for a number of behavioral events including tap, door opening, detection of enemy and/or friendly avatars, shooting, and friend or enemy elimination.

### 2.4 EEG Recording

The experiment took place in a sound-attenuated Faraday chamber. Dual-EEG was recorded by using two 60 channel EEG caps with Ag-AgCl electrodes arranged according to the 10% system [4] including midline and rows 1-8. Signals from both subjects were fed to a single amplifier (Synamp2; Neuroscan, TX) equipped with two distinct referential montages. This specially designed dual-EEG system ensured no delay between the EEGs acquired from each subject [5]. EEG signals were measured with the respective grounds located at FPz sites and the references at the corresponding linked mastoids. Impedances were maintained below 10 KΩ. Vertical and horizontal electro-ocular recordings were also collected to measure saccades and eye blinks. Additionally, noise prevention strategies (shielding and guarding of noise-emitting equipment) were applied to ensure that the behavioral apparatus did not corrupt EEG recordings.

### 2.5 Timing Validation and Syncing

To optimize the room clear software and to ensure that records of the avatar behavior and EEG data were accurately synchronized during experimental data collection, we developed an analog timing verification apparatus that served to synchronize the virtual room clear environment and the EEG system. The apparatus included time-telling (attached to virtual environment) and time-sensing elements (attached to EEG system). Time-telling elements were reserved patches on the corner of the screens that cycled through luminance increments at each refresh of the computer graphics (refresh rate, 60Hz), indicating the temporal progression of the room clear software. Time-sensing elements were photodiodes placed above the time-telling patches that transduced luminance values and transmitted them directly as an analogue signal to the EEG amplifier. Because EEG amplifiers are designed for accurate time registration, we took the analog trace of task progression provided by the photodiode as an objective measure of time-passing, and compared the temporal events of the room clear software against this standard.

During design of the software, measurement of time by the analog timing verification apparatus allowed us to identify and refine graphical processes and computations that slowed or perturbed execution of the videogame. For instance, we spared computer resources by identifying optimal programming of bullet trajectories. We also identified the Graphical Processing Unit (GPU) clock as the most reliable clock for use in the logging of events within the XNA framework. During experimental data collection, analog timers were used (offline) to resynchronize behavioral data collected in the room clear computer and the EEG measurements acquired and stored in its computer. Sections of the screens occupied with analog timers were masked to the subjects during the actual experiments.

### 2.6 Behavioral Analysis

Individual and collective performance measures were computed and analyzed from the log data (see section 2.3). Key performance measures were:

- leader entry readiness: delay between tap by follower to motion initiation by leader
- coordinated entry: delay between leader and follower room entry
- time to pie: delay between room entry and the initiation of pieing behavior
- time to shoot: delay between enemy detection and successful shooting
- time to reach corner: delay between room entry and corner reaching, normalized to distance
- entry slow-down: presence of motion deceleration in fatal funnel
- shooting slow-down: presence of motion deceleration during firing
- trajectory error: diversion of trajectory in fatal funnel
- gaze overlap at room clearing completion; percentage redundancy in room scanning
- time to clear room: delay between leader movement and room cleared

To determine coordinated as well as uncoordinated behavior, trials were divided into split-halves on the basis of the above performance measures, for coordinated entry, pieing individual and collectively, and corner of domination coordinated behavior. These variables also formed a behavioral context of broader temporal scale (room and building). Further, each time instant was characterized by a number of event-specific descriptors (see 2.3) which contribute to the behavioral context on shorter time scales. Finally, descriptors of role were added, such as leader (first avatar to enter) and follower; agent or observer of a given behavior; and executed entry pattern (buttonhook or crossover).

### 2.7 EEG Analysis

There is reason to believe that brain oscillations are the language of the brain and provide important dynamic "neuromarkers" (and neuromarker dynamics). By recording simultaneously between two brains, this study seeks to understand how neuromarkers are modulated in a team setting of some consequence.

Oscillations come in a variety of frequencies, themselves the intertwined result of temporal properties of neural circuitry (faster frequencies for shorter circuits, e.g. [6]) and functionally relevant time scales by virtue of interactions with the body and the environment (faster frequency for briefer functional processes). Within each of these frequency bands, transient dynamics is observed that has a typical duration of one-to-two cycles during waking EEG [1]. The present EEG analysis aims to identify how the self-organizing activity of the brain supports the many complex and temporally overlapping behavioral processes described in sections 2.2 and 2.6.

In order to analyze free-flowing behaviors in the ecologically valid task studied here, we developed a framework for *continuous* EEG analysis. Unlike typical methods, continuous EEG does not rest on iterative protocols that average neural activity over multiple realizations of the same sensorimotor events [7,8]. Instead, the goal is to uncover the link between spontaneously occurring behavioral variables and neural events, and further, to describe the optimal temporal distribution of neural activity for task performance (section 2.6). To do so, each subject's EEG is parsed into its constituting patterns of oscillatory activity, using specially designed spatiotemporal (segmentation of continuous, bandpass filtered EEG), spatiospectral (spatial patterns of Fourier power in short windows) and spatiotemporo-spectral techniques (wavelet spatial patterns). Co-occurrence between brain patterns and behavioral descriptors is then assessed with the goal of establishing causal relations between them.

Spatiotemporal analysis aims to identify synergistic patterns of brain activity as significant units of brain and behavior [9], or in other words, to read the correspondence between brain patterns and corresponding behavioral processes continuously, as in a musical score. Our analysis proceeds through four steps: frequency band identification, bandpass filtering, segmentation and classification. The resulting spatiotemporal patterns are compared between behavioral conditions. Frequency bands are selected on the basis of data-driven and conceptual constraints. When data indicates a specific oscillation of interest, for instance a neuromarker that differentiates between coordinated and uncoordinated social behavior (e.g. [5]), then that band is retained for subsequent analysis. To accommodate for inter-individual variability, this type of frequency selection is best accomplished on a subject-by-subject basis. If no prior information exists for specific oscillations, bands are chosen that meet the time scale of behaviors under investigation (e.g. faster frequencies for more transient behavioral processes). Broadband EEG is then filtered within this band with care (1) to choose a filter cutoff that prevents spatiotemporal pattern clipping and (2) to avert phase distortion with the use of zero-phase shift filtering techniques (phase information is essential to infer cortical self-organization; [1,3]). Results of these signal processing methods reveal a succession of transient spatial patterns that are segmented with visualization techniques [10] or algorithms based on the rotating wave approximation [11]. This parsing is followed by the classification of constitutive patterns and further analysis of their relation to behavioral descriptors.

Spatio-spectral analysis is a complementary method for the detection of dynamic neuromarkers, which is less precise temporally, but computationally faster. It addresses the spatial distribution of high-density EEG spectra. Because of the typical time scale of EEG patterns (1-2 cycles), Fourier analysis is performed in short segments (as short as relevant for the frequency band of interest). Short segments are generally conducive to poor spectral resolution, and high spectral resolution is critically required to distinguish closely overlapping neuromarkers [5]. To circumvent this limitation, "optimized zero-padding" is applied [12]: the signal is first split into epochs, the mean removed, multiplied with a Tukey window to minimize spectral leakage and padded with a suitable number of zeros to increase spectral resolution to the desired value. This technique preserves peak location of neuromarkers at the cost of spreading their power to a broader band (which is controlled by the optimized zero-padding technique). Resulting neuromarkers are examined for their correlation with behavioral descriptors.

Finally, a spatiotemporo-spectral approach was developed to explore more comprehensively the different frequency bands, their dynamic task-dependent modulation and their mutual interactions. Each EEG channel was subjected to a continuous wavelet transform to obtain time-frequency-power distributions. Complex Morlet wavelet was used as the mother function. The spatial distribution of high amplitude time-frequency energy was examined in relation to behavioral events: this technique does not assume frequency bands *a priori*, and is well-suited to reveal the natural time scales at which brain oscillations live during the course of room clearing task performance.

## 3 Summary

In the previous, we have presented a behavioral task that retains essential components of team work in the team-intensive task of room clearing. In addition to its obvious relevance for training in simulated environments, the task was designed to illuminate a novel dynamical framework for the analysis of brain and behavior intricacies. In a companion paper [13], we will present candidate neuromarkers for efficient room clearing and discuss key theoretical issues relating to successful team coordination.

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