Team Neurodynamics
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Temporal Sequences of Neurophysiologic Synchronies can Identify Changes in Team Cognition

Summary. Team neurophysiologic synchronies (NS) are the second-by-second quantitative co-expression of the same neurophysiologic / cognitive measure by individual members of a team. Previously we showed that the NS obtained from EEG-derived measures of engagement (EEG-E) were not random across a variety of teamwork situations, but changed with changing task demands. In this study we hypothesized that the expression of different NS may represent unobserved states of the team and that the sequence of NS expression may contain long memory relevant to the performance of the team. To test this hypothesis we performed hidden Markov modeling of the EEG-E NS streams from novice and expert Navy submarine piloting and navigation teams and show that the dynamic expression of states derived from these models identified short and long-term changes in the behavior of teams.

Keywords. Team Cognition, Problem Solving, EEG, Neurophysiologic Synchrony.

Introduction

The integrated thinking of a team is often described by the construct of team cognition (or team level macrocognition) (Warner et al, 2005). This is thought to be a dynamic construct that reflects the interrelated cognitions, behaviors and attitudes that contribute to team performance. Communication streams either verbal or non-verbal, synchronous, asynchronous or in the form of tags indicating who is speaking when, or to whom, are a natural product of teamwork and a primary data source for unraveling the dynamics of team cognition (Stahl, 2006). Communication analysis is laborious leading to the development of tools to both facilitate the interpretation of the flow (who is speaking) and content (what was said) of communication (Cooke, Gorman, Kiekel, 2008).

But communication may not be the only unobtrusive data stream available for studying team cognition in near real-time and in real-world environments. In an earlier study we hypothesized that as members of a team performed their duties each would exhibit varying degrees of cognitive components such as attention, workload, engagement, etc. and the levels of these components at any one time might reflect some aspects of team cognition (Stevens et al, 2009). Using EEG-derived metrics of engagement we identified neurophysiologic synchronies (NS) among these measures across team members and showed that on diverse tasks such as emotion recall, scientific problem solving and submarine piloting and navigation that the balances of these metrics across the members of the team were not random, but were associated with the team's changing activities and awareness of the situation. Given the second-by second nature of the measures their expression likely reflected the contributions of both individual (the person on the task) and team (the person in the group) cognition.

Analogous to the long memory phenomena embedded in some communication and other data streams (Gorman, 2005), there may also be information contained in the sequence of the neurophysiologic stream over longer time frames which may reflect more aspects of team cognition rather than individuals' immediate concerns with the task. In this study we have used hidden Markov modeling (HMM) of NS streams derived from SPAN teams to provide support for this hypothesis.

Tasks and Methods

These studies were conducted with navigation training tasks that are integral components of the Submarine Officer Advanced Course (SOAC) at the US Navy Submarine School, Groton, CT. The task is a high fidelity Submarine Piloting and Navigation (SPAN) simulation that contains dynamically programmed situation events which are crafted to serve as the foundation of the adaptive team training. Such events in the SPAN include encounters with approaching ship traffic, the need to avoid nearby shoals, changing weather conditions, and instrument failure. There are task-oriented cues to guide the mission, team-member cues that provide information on how other members of the team are performing / communicating, and adaptive behaviors that help the team adjust in cases where one or more members are under stress or are not familiar with aspects of the unfolding situation.

Each SPAN session begins with a briefing detailing the navigation mission. This is followed by the simulation which can last 60 – 120 minutes or more. Lastly a debriefing session occurs where teams reflect on their performance based on the dimensions of teamwork. This teamwork task is complex, requiring not only the monitoring of the unfolding situation and the monitoring of one's work with regard to that situation, but also the monitoring of the work of others. Three teams and 13 SPAN sessions have been studied.

We have defined team neurophysiologic synchronies (NS) as the second-by-second quantitative co-expression of the same neurophysiologic / cognitive measure by members of a team (Stevens et al, 2009, Stevens et al, 2010). Figure 1 shows a neurophysiologic measure being simultaneously detected at a point in time from the members of a hypothetical three person team where team member 3 expressed above average levels of this particular measure while team members 1 and 2 expressed below average levels.

Data processing for detecting and analyzing NS begins with the eye-blink decontaminated EEG files containing second-by-second calculations of the probabilities of High EEG-Engagement (EEG-E), Low EEG-E, and High EEG-Workload (EEG-WL) (Levendowski et al, 2001, Berka et al, 2004, Berka et al, 2007). High EEG-E levels represent periods of external awareness or engagement, while low levels may better represent introspective awareness.

This is followed by a normalization step, which equates the absolute levels of EEG-E of each team member with his own average levels. This identifies not only whether an individual team member is experiencing above or below average levels of EEG-E, but also whether the team as a whole is experiencing above or below average levels.

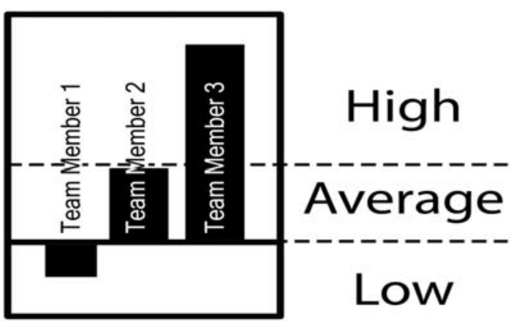

Figure 1. Expression of a Generic Neurophysiologic Measure by Individual Members of a three-Person Team

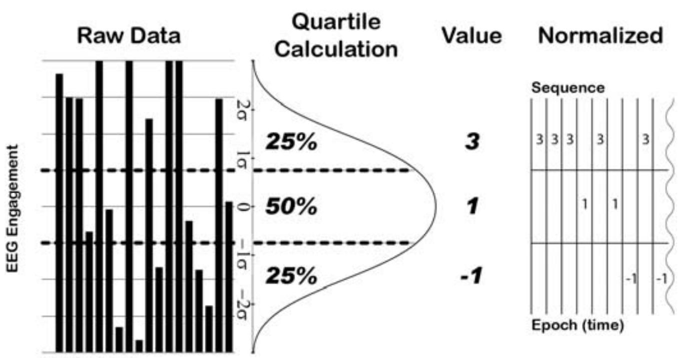

Figure 2. Normalization of Neurophysiologic Measures into Quartile Ranges.

In this normalization process (outlined for one individual in Figure 2) the EEG-E levels are partitioned into the upper 25%, the lower 25% and the middle 50%; these are assigned values of 3, -1, and 1 respectively, values chosen to enhance subsequent visualizations.

The next step combines these values at each epoch for each team member into a vector representing the state of EEG-E for the team as a whole, (this is shown for a team of 3 persons in Figure 3).

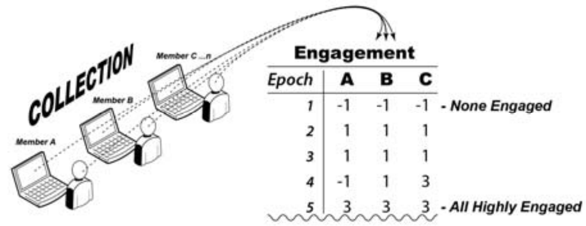

Figure 3. Creation of Team Performance Vectors. While the process is illustrated for three-member teams it can be expanded to include larger or smaller teams.

The second-by-second normalized values of team EEG-E for the entire episode are then repeatedly (50-2000 times) presented to a 1 x 25 node unsupervised artificial neural network. During this training a topology develops such that the EEG-E vectors most similar to each other become located closer together and more disparate vectors are pushed away. The result of this training is a linear series of 25 team EEG-E patterns that we call neurophysiologic synchronies.

Results

The first set of data is from an experienced submarine navigation team that conducted a 2 hr 45 minute SPAN session. Audio files were collected that allowed the second-by-second reconstruction of the teamwork discussions. Three crew members were fitted with the ABM B-Alert EEG headsets, the Quartermaster on Watch (QMOW), the Contact Coordinator (CC) and the Officer on Deck (OOD). The task began following a briefing period of 221 seconds and lasted until epoch (second) 6651. At epoch 7012 the debriefing period began. Routine events during the simulation included the updating of the ships position every three minutes, making decisions regarding encounters with other ships and generally satisfying the goals of the mission. Labeled above Figure 4B are several non-routine events that also occurred during the simulation which included a man overboard event (MOB), a period where the submarine skipper paused the simulation to address the team (Skipper Break) and a short Break after the simulation and before the Debriefing session began.

The characteristics of the NS are shown in Figure 4A and their second-by-second expression during the session is shown in Figure 4B. Here a bar mark is inserted for each of the 9684 epochs that represents the NS being expressed at each second.

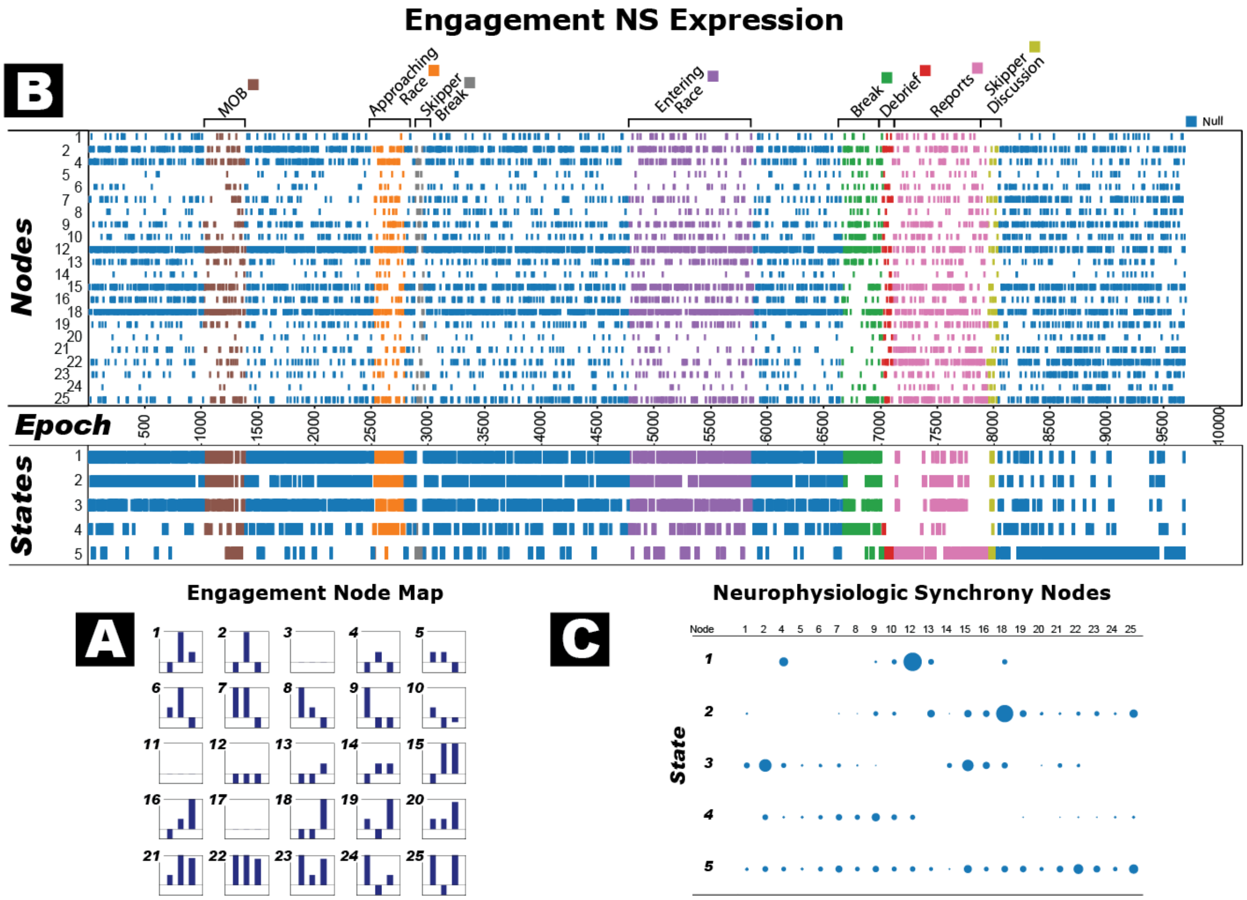

Figure 4. EEG-E Neurophysiologic Synchrony and NS State Expression for an Experienced Navigation Team.

From the density of the marks, NS # 12 was frequently expressed during the task. Referring to Figure 4A this NS represents times when all three team members showed below average levels of EEG-E. As discussed earlier (Stevens et al, 2009a) this does not necessarily mean that they are not engaged in the task, just that they were not externally engaged, i.e. they are more thoughtful or introspective. Similar to previous results, some NS like 7 and 21-25 were more frequent in the debrief section indicating that NS expression is sensitive to changes in the task.

Autocorrelation studies suggested that there may be a temporal component to NS expression over both short (seconds) and longer (minutes) periods of time (Stevens et al, 2009b). In this way the different NS being expressed over time might be viewed as output symbols from a hidden state(s) of a team, and if so the sequence may give some information about the hidden states the team is passing through. Hidden Markov modeling (HMM) would seem an appropriate approach for such modeling.

The NS data stream for the experienced submarine navigation team was segmented into sequences of 10 to 240 seconds generating NS symbol arrays. HMM were trained using these arrays assuming 5 hidden states as we have performed previously for modeling problem solving learning trajectories (Soller & Stevens, 2007). Training was for 500 epochs and generally resulted in a convergence of 0.0001. Next the most likely state sequence through the performance was generated by the Viterbi algorithm. The mapping of the individual NS to the different states is shown in Figure 4C. Some states like State 1 and State 2 are dominated by one or two NS with State 1 representing a condition when all team members showed low EEG-E. In State 2 the consistent feature of the NS emitted seems to be that team member 3 (OOD) had high EEG-E. State 5 in contrast is heterogeneous with regard to NS expression although it primarily shows periods where most members show high EEG-E (NS 20-23). The dynamics of State expression for the entire session is shown below the nodes in Figure 4B and show a large state shift near epoch 7000. While during the Task States 1-3 predominated, this shifted to State 5 during the Debrief.

The performance of a less experienced navigation team was processed similarly to generate 5 HMM states (Figure 5). This time there were six members being monitored by EEG. Similar to the experienced team, at the Task-Debrief junction there was a dramatic shift in State expression from States 2-4 to State 1 and then State 5. Referring to the NS patterns and State associations States 2-4 represent periods where EEG-E levels are high, and State 1 and to a lesser extent State 5 represent periods where EEG-E levels are low, the opposite from that observed with the experienced team.

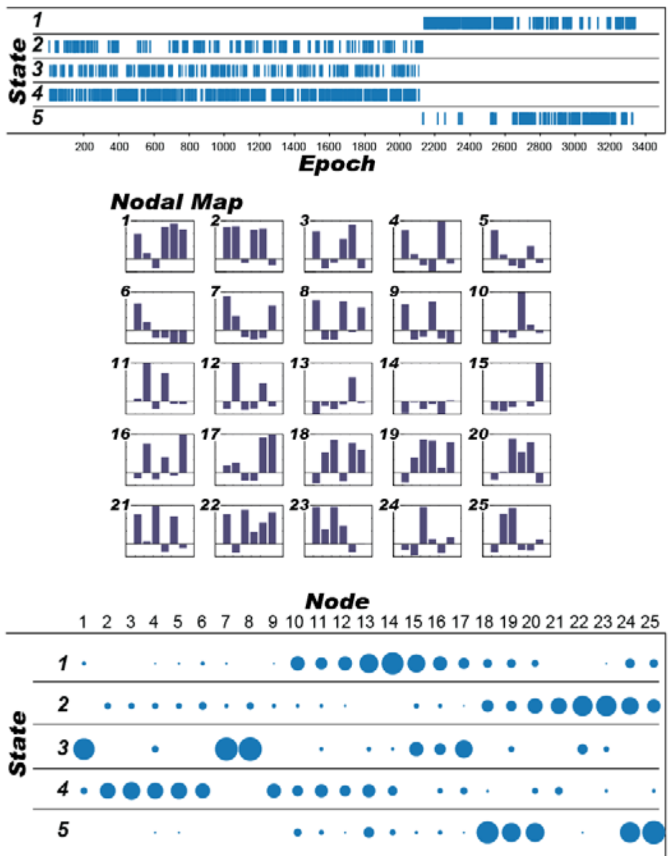

Figure 5. HMM State Profiles for a Novice SPAN Team.

These studies indicate that NS and modeled HMM states can detect large scale changes within the SPAN training session. We next wished to determine whether such transitions could be detected during shorter time periods. These analyses focused on non-routine periods of the simulation starting with the Skipper Break where the Skipper paused the simulation when the team was having difficulties approaching a hazardous section of Long Island Sound called 'The Race". (Figure 6A). Within a second the NS expression switched from the dominant States 1, 2 and 3 to State 4 and then State 5 where most members showed high levels of EEG-E, i.e. the team became externally engaged. After the short talk the team went back to the dominant expression of States 1-3 which represent a more introspective state of the team.

A second period is highlighted in Figure 6B for this in-depth analysis and this was the junction between the end of the simulation, through a short break, and into the debrief section (epochs 6400-9600).

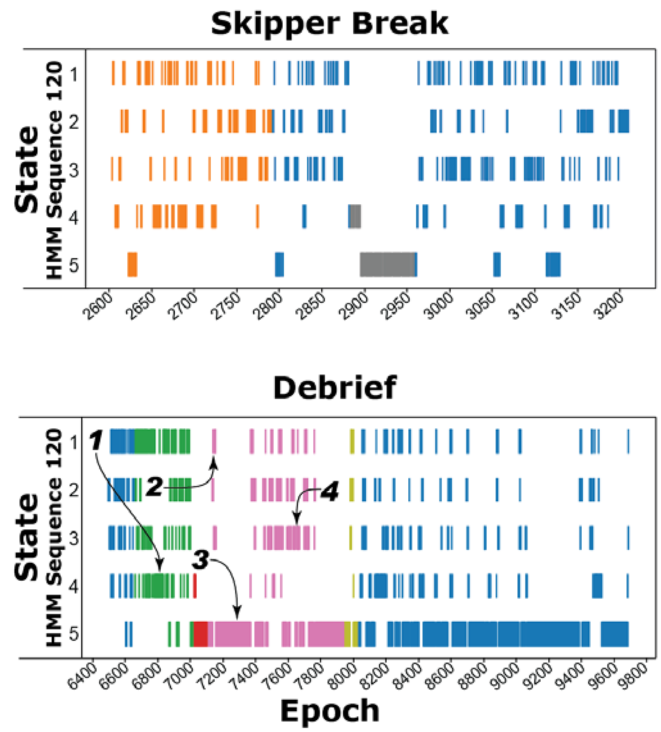

Figure 6. Details of NS State Expression during the Skipper Break and the Debrief Section. *Above:* The gray section indicates the Skippers' discussion. Below The green color indicates a break after the Task where the team was joking with the research staff (1). Red highlights the onset of the debrief with team reports occurring during the purple section.

Here the onset of the break is not as clearly demarcated by state transitions as it was with the Skipper Break. Instead as the team stands down they begin joking with the research staff (labeled as 1) and States 2 & 3 stop being expressed. A larger transition occurred when the debrief started and this was dominated by State 5, an externally aware mode. This section was followed by individual team member reports (labeled 3) which were generally State 5. For 30 seconds one team member criticized the team for excessive talking. During this time (labeled 2), the NS States switched to 1-3 and then returned to State 5 when this member finished speaking.

Discussion

Neurophysiologic synchronies represent a low level data stream that can be collected and analyzed in real time and in realistic settings. Our goal for studying NS expression is to be able to rapidly determine the functional status of a team in order to assess the quality of a teams' performance / decisions, and to adaptively rearrange the team or task components to better optimize the team. The neurophysiologic measure we have used for this study is a measure of engagement in the sense that high levels represent a state of external awareness while low levels better represent an introspective state. The current studies were motivated by our earlier demonstration of significant autocorrelations of NS expression over longer time lags (20 sec) suggesting that there may be a temporal component to their expression.

Several examples illustrate that the NS States may be a rapid and sensitive indicator of some aspects of team cognition. Both the experienced and novice SPAN teams studied showed sharp changes in NS States at the Task / Debriefing boundary indicating that their expression was sensitive to large changes in the task. While both groups showed these sharp transitions, the nature of the transitions were opposite. For most of the simulation the experienced team expressed more introspective states, (i.e. they were more involved with the task than other events in the room) and switched to a more externally aware state during the debrief and discussion. The novice team however was more externally aware during the task and became more introspective during the debriefing session. Whether these reflect general characteristics of novice / experienced teams awaits further studies.

While the transitions at the Task / Debrief boundary represent long lasting changes, the changes in NS State expression during the Skipper Break and Debrief show that changes can also occur quickly and may be able to highlight short term changes in team cognition.

An important question is the segment size chosen for creating the model and in studies not shown here it appeared that segments less than 30 seconds may not have sufficient information for developing good models. Possibly the use of overlapping segments would improve the models at these shorter times, but the need for longer segments (60-120 seconds) suggest that long memory effects may exist in the NS data stream (Gorman, 2005).

The usefulness of this approach will depend on the cognitive indicator chosen. In parallel studies we have similarly modeled an EEG-derived measure of workload and the NS (and the derived HMM States) with the same teams show very different dynamics from those described here with EEG-E. An important challenge will be relating the dynamics of any new cognitive measure to the team task to best determine what aspects of team cognition are being measured. It will be important to determine if the characteristics of cognitive measures defined by the performance of individuals map to the performance of teams.

While EEG has traditionally been viewed as a tool for studying individual cognition in the milliseconds to seconds range, the current approaches extend this utility to teams and over periods of minutes.

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