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# SUBMARINE NAVIGATION TEAM RESILIENCE: LINKING EEG AND BEHAVIORAL MODELS

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Advances in the assessment of submarine piloting and navigation teams have created opportunities for linking behavioral observations of team performances with neurodynamic measures of team organization, synchrony and change. Submarine navigation teams (n=12) were fitted with EEG headsets and recorded while conducting required navigation simulations. In parallel, their performances were assessed for team resilience by two evaluators using a team process rubric adopted by the Submarine Force. EEG models of team synchrony were created symbolically which identified times when there was increased across-team cognitive organization induced by the simulation and / or interactions with other crew members. One set of these organizations was observed in the 10 Hz EEG frequency band and coincided with the periodic activity of updating the ship's position (e.g. Rounds). There were also periods of increased team synchrony between 25-40 Hz which were present during some Rounds events but were more prominent with task changes or when the team was stressed. More resilient teams had fewer periods of team synchrony and these were of smaller magnitude than those found in less resilient teams. These results indicate that both routine and unexpected activities trigger increased neurophysiologic synchrony / coherence in teams and that periods of persistent synchrony may signal a team being challenged.

## INTRODUCTION

During social interactions across-brain neurodynamic synchronizations arise as teams perform the joint actions needed to accomplish a task. The rapid identification of these neurodynamic synchronies / coherences would support a better understanding of the factors responsible for inducing / inhibiting their formation and would provide new loci around which to structure teamwork and training. One conceptual approach for identifying these periods would be to view teamwork from the perspective of a group watching a video. As the video unfolds the visual and auditory elements it contains become cues that entrain the cognition of the group with inter-subject synchronizations occurring in the visual, auditory and cortical brain regions (Hasson, Nir, Levy, Fuhrmann & Malach, 2004; Sanger, Muller & Lindenberger, 2012; Tognoli & Kelso, 2013).

The differences between a group watching a video and being part of an active team arise when teammates interact with / in the scenario. They each then behave as part of a complex adaptive system that is free to interact with other complex adaptive systems. For submarine navigation teams these systems include other teammates, the changing environment, and other complex systems like other ships with their teams. Problems can arise when due to differences in their skillsets or prior training / experiences, the team members don't share the same interpretation of the situation. Such inconsistent shared mental models may predispose a team to being 'out of synch' and compromise its functioning. An equally problematic situation would be where all team members developed a local situation perspective and missed more global interpretations; i.e. tunnel vision.

We have been approaching these teamwork ideas from a neurophysiologic perspective using symbolic representations of the levels of EEG-defined measures of cognition. In these studies the degree of team neurodynamic synchrony / coherence varied with changes in the task (Stevens et al, 2011), in response to external task perturbations (Stevens & Galloway, 2014), or stress (Stevens, Gorman, Amazeen, Likens & Galloway, 2013). These studies also pointed to the existence of a continuum describing team synchrony at a neurodynamics level that ranged from rigid to flexible (Stevens et al 2013). The 'sweet spot' of this continuum (i.e. not too random or flexible) was where expert navigation team performances were located. While these studies provided a new perspective of teamwork in naturalistic settings, they were limited by the somewhat narrow instructor-specific performance evaluations which tended to be unbalanced in the performance constructs being rated. These evaluations also tended to be end-of-session summaries lacking the granularity needed for short-term mapping to significant neurodynamic changes in the teams.

In this study we have paired brain-wide team neurodynamic modeling with a standardized and vetted instrument for evaluating the resilience of submarine navigation teams. Combined, this has resulted in detailed maps of team synchronization and an approach for untangling the neurodynamic basis for high and low resilience teams.

### Submarine Team Behavioral Tool (STBT)

After two collisions in 2012 the Submarine Force undertook a substantial self-assessment effort. One finding was a widespread deficit in the ability of submarine watch teams to work together effectively. As a result of this report the Naval Submarine Medical Research Laboratory (NSMRL) began developing the Submarine Team Behaviors Tool (STBT) to formalize what has traditionally been a subjective assessment of a team's ability to work together effectively.

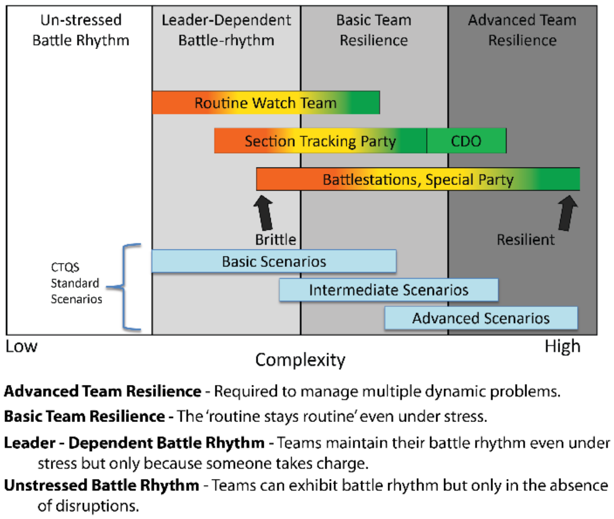


**Figure 1. Levels of Resilience vs. Watch Teams and Standard Scenarios.**

In developing an overall behavioral rating of team resilience, the STBT observers evaluated teams across a set of five practices that have provided new insights into how submarine tactical teams need to operate at sea. When one or more of these practices were absent, team problem solving suffered in some important way. These practices included Dialogue, Decision Making, Critical Thinking, Bench Strength and Problem-Solving Capacity. Each practice contained multiple behavior threads. For Decision Making these were Decisiveness & Leader Detachment; for Critical Thinking these were Planning & Time Horizon, Setting Context, Managing Complexity & Forceful Backup, etc. (Lamb, Lamb, Steed & Stevens, 2014). The presence / absence of these practices were linked to four Resilience Levels describing how teams of different experience perform in environments of different complexities (Figure 1).

In 2013 the parallel neurodynamics and behavioral research projects converged providing an opportunity to relate the neurodynamics of submarine teams to the behaviors affecting team resilience. One initial finding was a significant correlation at the level of the overall performance between the STBT team rankings and levels of EEG-defined cognitive measures such that the highest ranking teams also exhibited the highest levels of neurodynamic entropy, a measure of the flexibility / rigidity of teams (Lamb et al, 2014). This correlation suggested the opportunities for more refined within-performance analyses to temporally map the neurodynamics of resilient and brittle teams.

The hypotheses for this study were:

1. Periods of Submarine Piloting and Navigation (SPAN) team synchrony can be identified by symbolic neurodynamic modeling of individual EEG frequency bands.
2. Neurodynamic fluctuations of different EEG frequencies can distinguish routine and non-routine team navigation activities.
3. Quantitative and qualitative differences in team neurodynamic synchrony occur between brittle and resilient SPAN teams.

## METHODS

Eye-blink and artifact decontaminated EEG data was collected from electrodes Fz, F3, F4, Cz, C3, C4, P3, P4 and POz using the X-10 B-Alert™ series headsets and hardware (Advanced Brain Monitoring, Inc., Carlsbad, CA) and processed into forty 1 Hz power spectral density (PSD) bins. Symbolic neurophysiologic states were constructed from each frequency by partitioning the second-by-second EEG-PSD of each performance into the upper, lower, and middle 33% values; which were assigned values of 3, -1, and 1. These values were combined from each member of the team to create vectors that were classified by artificial neural networks as described previously (Stevens et al, 2013) creating a symbolic state space like that shown for a five-person team (Figure 2). Here each of the 25 symbols represents a possible team neurodynamc state and individual histograms show the levels of the neuromarker being studied for each team member. The second-by-second expression of these symbols, termed Neurodynamic Symbols (NS) served as the primary data for identifying periods of team synchrony.

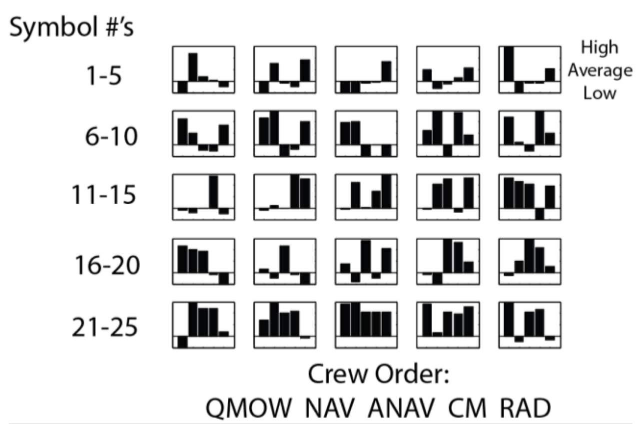


**Figure 2. Symbol State Space for a 5-Person Team. The histograms in each symbol show the relative levels of the neurodynamic measure being modeled for each of the five crew members.**

These symbols showed not only the relative EEG power levels for each person in the team, but also the level in the context of the levels of every other team member, *and*, within the immediate context of the task. Normalizing values over an entire performance also provided physio-behavioral responses across a variety of task situations / loads (Fishel, Munth & Hoover, 2007). This process was repeated for each of the forty 1 Hz bins at the following EEG dipoles: FzP0, FzC3, CzP0, C3C4 and F3Cz. A global NS Entropy Map was also created by averaging the values across all dipole maps.

Sequential symbol expressions during teamwork performance showed uneven symbol distributions and quantitative estimates of the magnitude, duration and frequencies of these distributions were calculated from the Shannon entropy of the data stream over a moving window (100 seconds for this study) (Stevens & Galloway, 2014).

It is important to emphasize that the fluctuating dynamics of NS entropy are not necessarily a reflection of the power levels for the different Hz bins across the team. While there may be points when all team members had high or low levels of a neuromarker, periods of team synchrony should be thought of as times where there was increased across-team cognitive organization in response to the simulation and /or interactions with other crew members, with the lower the NS entropy the greater the organization.

## RESULTS

The results presented contrast two junior officer navigation teams. The first was rated by the STBT evaluators as having Unstressed Battle Rhythm which is a brittle resilience level (Team 1), while the second team (Team 2) had a more advanced level of resilience, i.e. Basic Team Resilience. These are two of twelve teams that have been analyzed and are presented as they represent opposite ends of the resilience spectrum. The features presented below occurred to a varying degree in all performances.

*Team 1 Performance Notes:* Both evaluators indicated that leader presence was largely absent in Team 1. Commands were often informal and conversationally phrased or posed as a question. Task awareness was listed as being absent. This performance had the usual Briefing and Debriefing segments that bookended the Scenario, but was unusual in that midway through the performance, at ~ 2100 seconds, the submarine approached shoal water and grounded, a catastrophic event. The simulation was paused, the team briefed by the instructor, and the submarine was re-positioned in the simulation and the exercise continued.

Neurodynamic symbol streams were created for each of the forty 1 Hz EEG frequencies and the entropy profiles generated. The forty entropy profiles were aligned to create a three dimensional contour map where the darker contours represented periods of reduced NS entropy. Reduced entropy results from a more limited expression of NS symbols over the moving 100 second time window and indicates a more organized or rigid state, i.e. increased team synchrony.

Episodes of decreased entropy around 10 Hz were a prominent feature of the NS entropy map (Figure 4A). These were also seen as a dip in a plot of NS entropy vs. EEG frequencies (Figure 4B) which was lost when the 10 Hz NS symbol stream was randomized before entropy modeling. The 10 Hz entropy periodic fluctuations had a temporal similarity with the Rounds process in that they were absent during the Debriefing and the Pause segments and similar decreases during the Briefing were associated with the initial establishment of the submarine's position before the simulation began (Figure 4C).

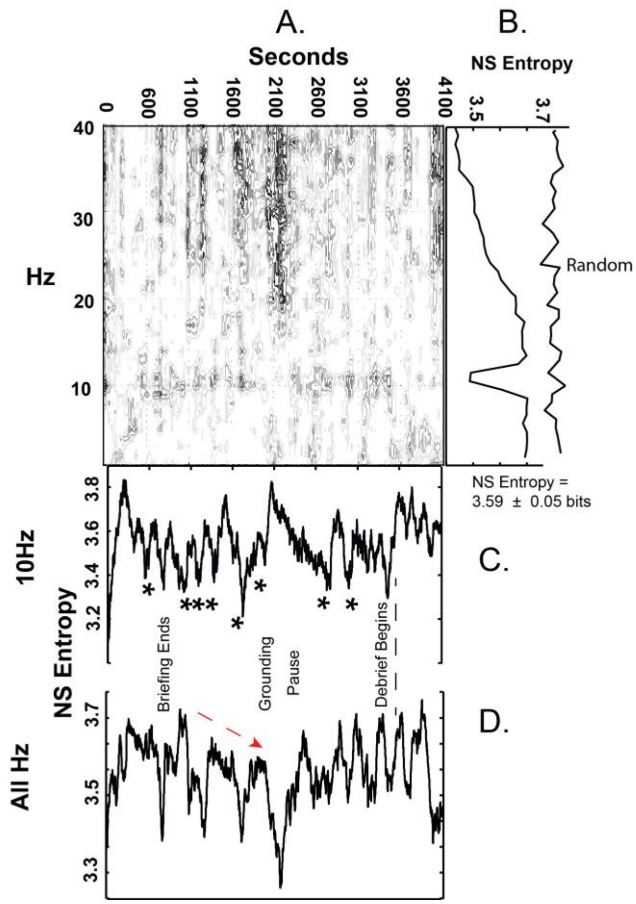


**Figure 4. Neurodynamic Entropy Analysis. A) Neurodynamic symbol streams were created for EEG frequencies 1-40 Hz and the NS entropy calculated over a 100 second moving window; the dark contours indicate periods of decreased NS entropy. B) The average NS entropy levels are plotted for each EEG frequency. The line marked *Random* resulted when the NS data were randomized before modeling. C) The average NS entropy was calculated each second for the 10 Hz frequency band; the asterisks identify the 'Mark Round' calls. D) The average NS entropy is shown for frequencies 1-40 without the 10 Hz band.**

Visual inspection suggested close matches between the calls to 'Mark Rounds' and the periods of minimum entropy in the 10 Hz frequency profile. An analysis of variance indicated that the 10 Hz NS entropy levels during the 10 seconds prior to the Mark Rounds calls were significantly lower than those in the 10 seconds before the '1 minute to next Rounds' or the remaining seconds during the Scenario (Mark Rounds = 3.45 ± 0.1 bits, 1 Minute to Rounds = 3.59 ± 0.1 bits, Remaining seconds = 3.50 ± 0.1 bits); multiple comparisons by LSD were significant at the 0.05 level.

Increased team synchrony was also seen in the 20-40 Hz frequencies (beta and gamma waves) which had various magnitudes and durations, the largest coinciding with the simulation Pause immediately after the grounding. For the 15 – 17 minutes prior to the grounding there was a progressive decrease in the NS entropy in the 20-40 Hz bands as indicated by the arrow in Figure 4D. The decrease was not the result of any major event, but reflected an accumulation of smaller events / situations like a degrading GPS signal multiple calls for backup soundings, or being 100 yds right of track, and then left of track as the crew prepared for a course change. These culminated in a Left Full Rudder call which was misinterpreted as a Right Full Rudder call leading to the grounding. After a short briefing the simulation continued without incident. During the second half of the performance the NS entropy in the 20-40 Hz frequencies increased although a regular Rounds rhythm was not re-established at the 10 Hz. Frequency.

*Team 2 Performance Notes:* The evaluators reported that Team 2 engaged in hypothesis derived situation data with leaders providing high level contextual information. Decisions were made under uncertainty and decisive language was consistently used. The simulation was performed under conditions of reduced visibility which was further complicated by the initial positioning of the submarine 2000 yards to the west due to a technical problem. These created major challenges for the team resulting in a possible collision with a merchant ship at ~2600 seconds and with a sailboat at ~4000 seconds.

In contrast to the NS entropy profiles of Team 1 (Figure 4 C & D), the NS Entropy map of Team 2 showed a mostly undisturbed and high entropy profile (Figure 5 C & D). The 10 Hz decreased entropy profile that was seen in Figure 4 was largely absent. The head-on interaction with the merchant ship at ~2600 seconds coincided with a detectable decrease in the 0-40 Hz entropy profile while the decrease during the interaction with the sailboat was greater. There was also a short, high magnitude 10 Hz entropy decrease at ~ 3800 seconds when the team discovered the instrument misalignment and that they were out of position.

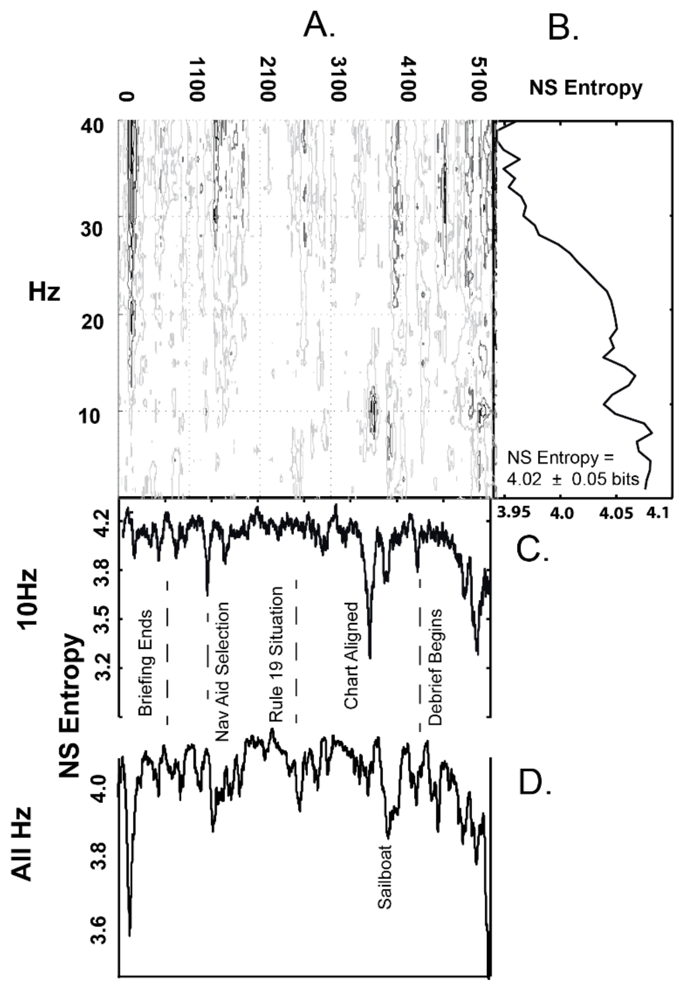


**Figure 5. Neurodynamic Entropy Analysis. A) Neurodynamic symbol streams were created for EEG frequencies 1-40 Hz and the NS entropy calculated over a 100 second moving window; the dark contours indicate periods of decreased NS entropy. B) The average NS entropy levels are plotted for each EEG frequency. C) The average NS entropy was calculated each second for the 10 Hz frequency band. D) The average NS entropy is shown for frequencies 1-40 Hz minus the 10 Hz band.**

## DISCUSSION

The goal of this study was to begin developing detailed linkages between the behavioral observations of evaluators and neurodynamic measures of teams performing submarine navigation tasks. The approach taken was designed to identify periods where the team members developed a coherence or synchrony at different EEG frequencies and electrodes. Neurodynamic synchrony is used here in the sense of a persistent temporal relationship in the expression of EEG rhythms across members of a team.

Most teams analyzed had characteristic NS entropy features the first being the periods of low entropy during the Briefing and Debriefing segments. This was not surprising as the teams are behaviorally the most organized during the Debriefing when all team members actively participate in the performance critique. The Briefing segment is more a hybrid of the Scenario and Debriefing segments with periods of common discussions intermixed with individual instrument calibrations and small group activities.

During the Scenario there were two consistent patterns in the neurophysiologic synchrony. First, there were bands of decreased NS entropy in the 10-11 Hz (alpha-waves) frequencies which were present to varying degrees during the Scenarios and absent during the Debriefing. Converging evidence suggested that these were related to the periodic task of taking Rounds. Rounds are periods of intensive team coordination which updates the position of the ship and at the same time coordinates the formation of a more uniform mental model / situation awareness in the team. By high spectral EEG analysis the region between 10-11 Hz contains multiple neuromarkers associated with social coordination. These markers include the Phi complex which are recruited during intentional social coordination, Mu medial which is suppressed during social interaction, but rebounds during self-produced movement, and alpha which is decreased by visual input or vision of a team member's movement (Tognoli & Kelso, 2013). The limited EEG electrode array used in these studies precluded a closer examination of this region.

How do our findings relate to ideas of team performance and resilience? Increasingly the field of resilience engineering is viewing incidents less as point in time events and more as a temporary inability of the team to effectively cope with the situation complexity. Team 1 serves as an illustration of the increasing inability of the team to resolve multiple small problems which eventually cascaded into a catastrophic event. While they performed Rounds on time and for the most part accurately (i.e. the routine made routine), they were more challenged by unexpected changes in the speed and direction of the current.

To some extent this reframing of the ideas of safety and resilience needs viewing from the perspective of what happens when things go right, i.e. looking at the range of human performance variability that constitutes successful team adaptations (Rankin, Lundberg, Woltjer, Rollenhagen & Hollnagel 2013). Comparing the brittle vs. resilient teams' neurodynamically starts to provide this perspective with teamwork measures that reveal performance variability as points along a continuum of adaptations ranging from regular to exceptional. Periods of high team synchrony were not frequent, occurred when the teams needed to focus, and this was more common in Team 1. There were other periods of team synchrony during more routine events like Rounds which had a smaller magnitude and duration. The multifractal structure of the NS entropy profiles suggests the existence of other periods with even smaller levels of team organization (Likens, Amazeen, Stevens, Galloway & Gorman, 2014). We hypothesize that this scale of NS entropy fluctuations represents the teams' neurodynamic responses to events along the adaptation continuum from regular to exceptional. Consistent with this hypothesis is the correlation between the level of team resilience and NS entropy (Lamb et al, 2014) and the differences in NS entropy between experienced and less experienced navigation teams (Stevens et al, 2013).

These findings could support training in several ways. First, the absence of strong team synchrony during periods when the evaluators perceived a risky situation may indicate that the team did not recognize the gravity of the situation. Alternatively, a reverse correlation approach could be used to identify periods of significance to the team, i.e. situations where they are not confident which may have gone undetected by the evaluators. Rapid modeling of team synchrony, and identification of either situation would make it easy to provide specific and timely feedback on identified behaviors. This would also begin to provide a pathway for using data and statistics to build better watch teams.

## ACKNOWLEDGEMENTS

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