Team Neurodynamics by The Learning Chameleon, Inc.

Team Resilience: A Neurodynamic Perspective

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Abstract. Neurophysiologic models were created from US Navy navigation teams performing required simulations that captured the crews' dynamic responses to the changing task environment. Crew performances were simultaneously rated by two expert observers for team resilience using a team process rubric adopted by the US Navy Submarine Force. Symbolic neurodynamic (NS) representations of the 1-40 Hz EEG amplitude fluctuations of the crew were created each second displaying the EEG levels of each team member in the context of the other crew members and in the context of the task. Quantitative estimates of the NS fluctuations were made using a moving window of entropy. Periods of decreased entropy were considered times of increased team neurodynamic organization; e.g. when there were prolonged and restricted relationships between the EEG- PSD levels of the crew. Resilient teams showed significantly *greater* neurodynamic organization in the pre-simulation Briefing than the less resilient teams. Most of these neurodynamic organizations occurred in the 25-40 Hz PSD bins. In contrast, the more resilient teams showed significantly *lower* neurodynamic organization during the Scenario than the less resilient teams with the greatest differences in the 12-20 Hz PSD bins. The results indicate that the degree of neurodynamic organization reflects the performance dynamics of the team with more organization being important during the pre-mission briefing while less organization (i.e. more flexibility) important while performing the task.

Keywords: Team Neurodynamics, Resilience, EEG, Submarine

1 Introduction

Resilience is a construct that is not well understood in individuals and teams. As a phenomena, resilience is closely tied to the cognitive concepts of attention, memory and decision making, all of which show decrements during stressful conditions [1]. Estimates of the level of team resilience can be made from the short-term decisions and communications that a team makes, and in time these accumulate into more accurate estimates. What is needed however, are more prospective explanations of teams' responses to disruptions of their rhythm that can illuminate new paths for team assessment and training. These explanations will likely come from descriptions of resilience that are linked to physiologic understandings of individual and team responses to stress.

One way to search for these explanations would be to focus on fundamental biologic and physical principles and computations that dynamically expand into cog-

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nitive and behavioral processes that guide teamwork across large scales of training and performance [2]. Rhythm may be one such principle for teams. Scientifically, over shorter periods of time the fluctuating rhythms of teams manifest as a fractal structuring of communication [3], or as the multifractal structure of team neurodynamic rhythms [4]. Disruptions to ongoing team rhythms often occur at major task junctions or when the resilience of a team is challenged [5]. These events force teams to adapt by changing their 'normal' operating rhythm. These changes in team rhythms following adaptive behavior are often nonlinear and punctuated by the emergence of new organizational structures and the establishment of new rhythms [5]. The important point is that rhythms do not arise de novo in a team, i.e. the initiation of a team rhythm requires interaction with both a task as well as other team members.

For several years we have focused on developing team-wide temporal data streams using symbolic representations of various neurodynamic measures. These studies have shown that 1) the neurodynamic rhythms of six-person US Navy submarine navigation teams are measurable and entrained by the task [6], 2) the structure of these rhythms is multifractal, resulting from the meso and micro responses of teams to changes in the task and the sharing of information across the crew [4], and 3) quantitative differences in team's neurodynamic rhythms may be linked with team expertise. Consistent with the nonlinear dynamical systems concepts of elasticity and rigidity in complex adaptive systems [7], the expert navigation teams were positioned at a neurodynamic point midway between rigid and elastic organization [5,8]. These findings suggest the existence of fundamental processes related to neurodynamical rhythm and organization that quantitatively track across the novice-expert continuum.

In this study we take advantage of naturally occurring perturbations to team function to link neurodynamic measures of within and across-brain team activities with observational measures of team performance. This study became possible when the Naval Submarine Medical Research Laboratory (NSMRL) began an extensive effort to provide the Submarine Force with a way to improve operational performance by not focusing on human error per se, but on human variability which not only considers the action, but also the context within that action occurred [9,10]. The result was the development of the Submarine Team Behaviors Tool (STBT) which provides an observational means for measuring team performance (Submarine Team Behaviors Tool Instruction Manual, COMSUBLANT / COMSUBPAC N7, December 6, 2013). Our goal was to link the information / organization structures in neurodynamic data streams with expert observational ratings as a way for understanding the neurophysiologic basis of team resilience.

2 Methods

2.1 Submarine Piloting and Navigation Simulations (SPAN)

Each SPAN session contains three segments. First there is a Briefing (~10-30 min) where the training goals of the mission are presented along with the ship's position, other contacts in the area, weather, sea state and the Captain's orders for safe operation. The Scenario (~50-120 min) follows and is a more dynamic task containing easily identified processes of teamwork along with other processes less well defined. The Debrief section (~20-30 min) is an open discussion of what worked, what other options were available and long and short term lessons. The Debrief is the most structured training with individual team member reports. The task for the team was to safely pilot the submarine to / from a harbor while avoiding collisions and groundings. While functioning as a team, officers also had individual task responsibilities that helped determine the position of the ship and possible hazards; for instance the radar operator continually adjusted the radar scope, identified and tracked ships and hazards, and maintained a mental model of the situation.

2.2 Submarine Team Behaviors Tool (STBT)

Development of the STBT originated as a study of submarine mishaps to understand the impacts of emerging complexity on human performance. During the study, certain team performance factors were found that degraded the performance of submarine tactical watch teams. Research at the Naval Submarine Medical Research Laboratory (NSMRL) in Groton, CT indicated that, in addition to technical skills, deliberate and effective team practices are necessary to manage the wide variety of increasingly complex problems that occur during tactical operations. The intent was to go beyond the typical lessons learned about human error and provide the Submarine Force with a way to improve operational performance going forward by not focusing on human error per se, but on human variability which not only considers the action, but also the context within that action occurred [9]. The result was the development of the Submarine Training Behaviors Tool (STBT) which provides an observational means for measuring team performance.

The STBT was accepted by the Submarine Force in late 2013; the near-term objectives for this initiative included improving the quality and consistency of feedback provided to submarine Commanding Officers regarding their teams' performance, providing a model of what 'good' looks like for crews to aspire to, and defining an end state to guide additions to the existing training continuum.

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 while for Critical Thinking these were Planning & Time Horizon, Setting Context, Managing Complexity, and Forceful Backup, etc. 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).

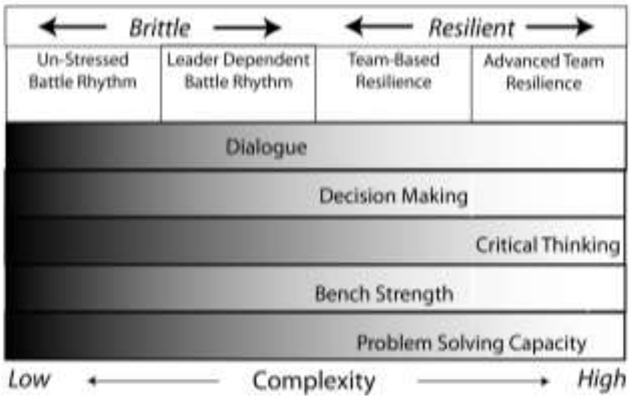

Fig. 1. Overview of STBT ratings. The levels of team resilience (in descending order) were 1) Advanced Team Resilience where the teams could manage multiple dynamic problems; 2) Team-based Resilience where routine activities can be managed even during stress; 3) Leader-dependent battle rhythm where the teams retain their rhythm even under stress, but only because someone takes charge, and; 4) Unstressed battle rhythm where teams exhibit a rhythm, but only in the absence of disruptions. Evaluator rankings were made on a scale from 0 (low) to 4 (high) and the reliability between the two evaluators was 0.89.

2.3 Electroencephalography (EEG)

The X-10 wireless headset from Advanced Brain Monitoring, Inc. (ABM) was used for data collection. This wireless EEG headset system included sensor site locations: F3, F4, C3, C4, P3, P4, Fz, Cz, POz in a monopolar configuration referenced to linked mastoids; bipolar derivations were included which have been reported to reflect sensorimotor activity (FzC3) [11], workload (F3Cz, C3C4) [12], and alpha wave components of the human mirror neuron system [13]. Embedded within the EEG data stream from each team member were eye blinks which were automatically detected and decontaminated using interpolation algorithms contained in the EEG acquisition software [14]. The EEG power spectral density (PSD) values were computed each second at each sensor for the 1 – 40 Hz frequency bins by the B-Alert Lab PSD Analysis software.

2.4 Modeling Neurodynamic Symbol Streams

Our goal was to develop neurodynamic data streams that had internal structure(s) with temporal information about the present and past organization, function and performance of the teams. Treating data from multiple time series as symbols is one approach that has been useful for discovering data patterns in temporal data streams [15, 16]. For team dynamics, the state of the team can be represented by a symbol showing the relative EEG marker levels for each person (Figure 2a). The importance of a symbolic team representation is that it shows the marker levels for each team member, the level in the context of the levels of other team members being studied, and associates it with the changing context of the task.

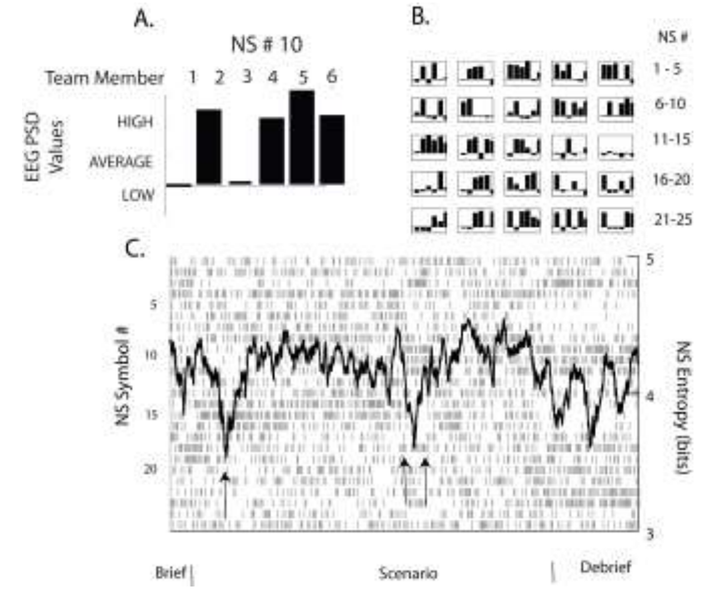

Fig. 2. Steps for extracting low-dimensional, single-trial neurodynamic organization information from the 10 Hz EEG levels of a six-member submarine navigation teams. (a) This symbol represents times when crew members 1 & 3 had below average 10 Hz EEG levels and the remaining crew had above average levels. For this example the 10 Hz PSD values was chosen. (b) The twenty-five-symbol state space is shown with the symbols assigned numbers in rows. (c) Each row represents the expression of the twenty-five NS from the 10 Hz frequency bin. These patterns are overlaid with a trace of the Shannon entropy of the NS symbol stream.

The temporal expression of these symbols for a SPAN performance is shown in Figure 2c where each row shows the temporal expression of the twenty-five NS symbols; the expression of was not uniform. The first large NS entropy fluctuation (single arrow) was linked with an increased expression of NS #15-16 and the near absence of NS #11-12. Referring to Figure 2b NS #11-12 represented periods when many crew members had high 10 Hz EEG levels while NS #15-16 represented times when 10 Hz EEG power levels were low across the team. The second fluctuation (double arrows) showed a reciprocal expression with increased NS #9-11 and decreased NS #15-16. Quantitative estimates of the changing symbol dynamics are shown by the trace in Figure 2c; these estimates were calculated and quantitated by measuring the Shannon entropy over a sliding window of 100s [5, 17]. Performance segments with restricted symbol expression had lower entropy levels, while segments with greater symbol diversity had higher entropy. As reference points, the maximum entropy for 25 symbols is 4.64, which decreases to 4.0 when only 16 symbols are expressed. Periods of decreased entropy were operationally considered as times of increased neurodynamic organization across the team.

3 Results

3.1 NS Entropy / Frequency Profiles for SPAN Segments

The NS entropy levels for twelve SPAN teams were determined for the Briefing, Scenario and Debriefing segments across the 1-40 Hz EEG frequency bands (Figure 3). The highest average NS entropy (i.e. the least team neurodynamic organization) occurred in the Scenario segments while significantly lower entropy levels (i.e. more team neurodynamic organization) were observed in the Brief and Debrief segments (F = 3.52, df = 2, p = 0.04).

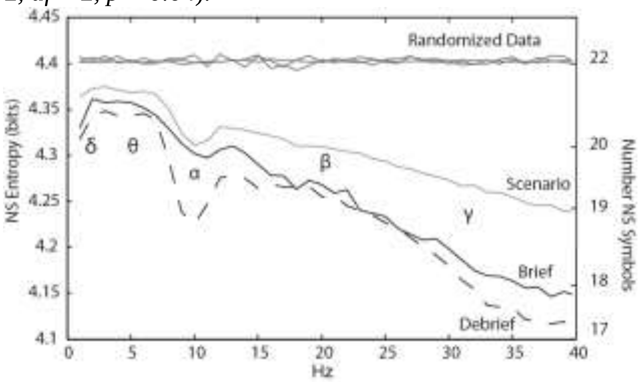

Fig. 3. EEG frequency profiles team NS entropy and averaged PSD levels. The NS entropy streams from twelve SPAN performances were separated into the Brief, Scenario and Debrief segments and the frequency-entropy profiles were generated.

The NS entropy profiles were the highest at the lower (3-7 Hz) frequencies and progressively decreased towards the 40 Hz band. In each of the three training segments there was also a significant NS entropy decrease associated with the 8-13 Hz frequency region (i.e. the α band) with the NS entropy in the 10 Hz PSD bin being significantly less in the Debriefings than in the Briefings or Scenarios (F = 7.88, df = 2, p = 0.002). Surrogate data testing was performed in all experiments. In this process the symbols in the NS data streams were randomized before calculating the entropy; as expected, this uniformly removed the NS entropy fluctuations.

3.2 Correlations Between NS Entropy and STBT Ratings

The combined data from the twelve STBT teams in Figure 3 suggested that neurodynamic organizations were frequent during SPAN teamwork, raising the question of whether these organizations had significance in the context of team performance. Seven of the twelve SPAN teams in this study met the criteria of 1) having two independent STBT evaluator ratings, 2) the EEG data from the complete performance (i.e. the Briefing, Scenario and Debriefing segments) was available for modeling, 3) EEG was collected from at least five crew members, and, 4) each of the training segments was at least 500 seconds long.

The correlation between the NS entropy levels of the entire performance and the STBT evaluation scores was not significant (r = -.28, p = .53). Correlations were then conducted using the NS Entropy levels of the Briefing, Scenario and Debriefing segments. Between group ANOVA comparisons were significantly different (F = 17.4; df = 2, p< 0.001), and a multiple comparisons analysis by LSD indicated that the Brief, Scenario and Debrief segments differed at the 0.05 level. (Figure 4). Also shown in this figure are the segment-wise correlations at the different EEG sensor bipoles.

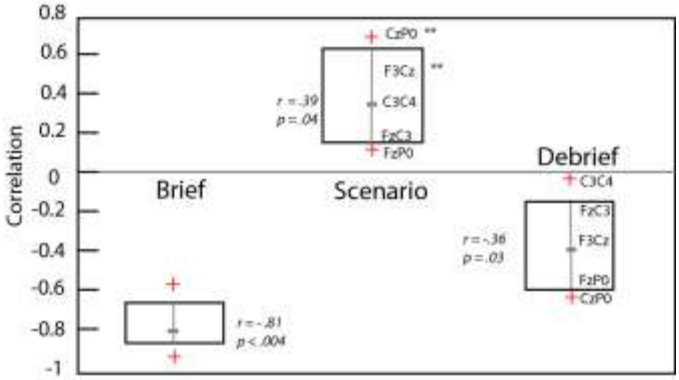

Fig. 4. Correlations between STBT ratings and NS entropy levels. The NS entropy levels for the C3C4, FzP0, FzC3, CzP0, F3Cz sensor pairs for the Brief, Scenario and Debrief segments were correlated with the STBT ratings (*n=7*). The Scenario correlations at the CzP0 and F3Cz were significantly (p < 0.05) greater than the correlations at the C3C4, FzC3 and FzP0 sensors.

During the Briefing, there was a significant negative correlation between the NS entropy and the STBT ratings. This means that higher STBT ratings correlated with lower NS entropy levels. As decreased NS Entropy indicates more neurodynamic organization the results show that the more resilient teams were neurodynamically more organized than the less resilient teams (Figure 4).

During the Scenario there was a positive correlation between STBT ratings and NS Entropy indicating that high resilience teams were neurodynamically less organized than the lower resilience teams. The team NS entropy that was calculated from the CzP0 or F3Cz EEG sensor bipoles was significantly higher than the NS Entropy from the FzP0, FzC3 or C3C4 sensor combinations. During the Debriefing there was a negative correlation between the NS entropy and STBT ratings of the teams.

Correlations profiles were then constructed for each of the EEG 1 Hz frequency bins for the Briefing, Scenario and Debriefing performance segments to better situate the correlations in the EEG frequency spectrum. With the CzP0 EEG sensor combination, the most significant correlations with the STBT ratings were the negative correlations in the ~20-40 Hz bins of the Briefing segment (Figure 5). Most of the correlations between 27 – 34 Hz bands were significant at the p < 0.05 level. Similar negative correlations were also seen in the Debriefing. During the Scenario segment the NS entropy / STBT rating correlations were high with the most significant correlations between ~10 and 20 Hz.

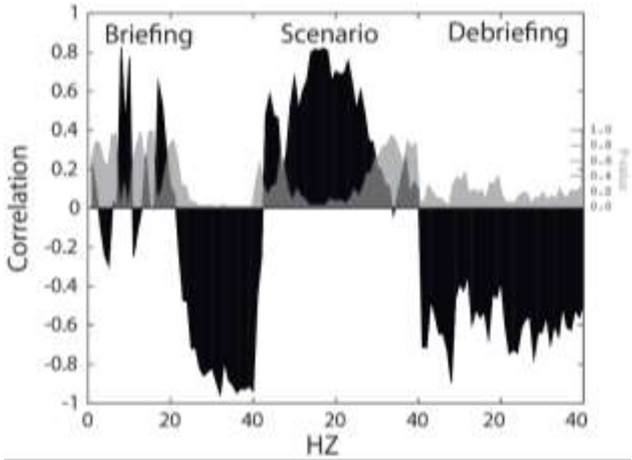

Fig. 5. Correlations between the STBT evaluation scores and the EEG PSD levels for the 1 Hz frequency bins from CzP0 (n=7). The *p*-values for each correlation are shown in light gray. The Briefing, Scenario and Debriefing segments are labeled for each of the forty 1 Hz bins.

Figure 6 plots the average NS entropy levels for resilient and less resilient teams as a function of frequency bins. In the Briefing segment there were significant negative correlations (r > 0.5) particularly in the 25-40 Hz region (p ranged from .003 to .05). The positive correlations in the Scenario were most significant (r > 0.7) in the 12-17 Hz frequency range with p values ranging from 0.03 to 0.05).

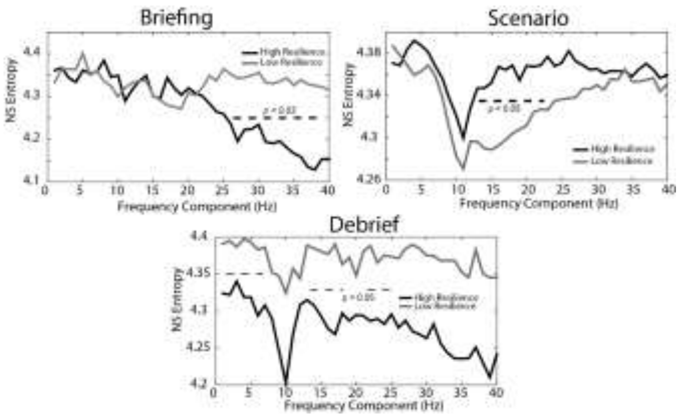

Fig. 6. Correlations between the STBT evaluation scores and the EEG PSD levels are plotted (dark gray) for four high and three low resilience team performances. The *p*-values for each of the correlations are shown in light gray. The EEG power levels are from the CzP0 bipolar combination and correlations were performed for each 1 Hz bin in the Briefing, Scenario and Debriefing segments of the seven teams. The dotted lines indicate significant differences.

4 Discussion

In this study the linkages between the behavioral observations of evaluators and neurodynamic measures of teams performing submarine navigation tasks were explored. Neurodynamic organization is used in the sense of persistent temporal relationships in the quantitative expression of EEG rhythms across members of a team. These relationships are captured symbolically as team cognition evolves in parallel with the task. Data streams of these symbolic neurodynamic relationships provide a temporal view of how the team and its members responded to periodic routines and unexpected challenges

Most teams had characteristic NS Entropy features, the first being the periods of lower NS 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.

The neurodynamic organizations (i.e. periods of decreased NS Entropy) of teams were observed in all EEG frequency bands but were least in the theta (θ) and delta (δ) regions. Theta oscillations are important for processing spatial information and for memory encoding and retrieval, and intuitively these activities seem more within brain rather than across-brain cognitive functions. Delta oscillations are primarily seen during sleep, although recently a role in suppression of external distracting information has been suggested [18]. The neurodynamic organizations in the alpha (α) region dominated the NS entropy spectral profile for SPAN teams. This dominance of alpha may in part be due to the task, as prior studies of teams performing more action-oriented tasks showed little neurodynamic organizations in the alpha region, and more in the beta region (Stevens & Galloway, under review). The alpha band oscillations have known heterogeneity with regard to social coordination markers. The μ medial, the phi complex and occipital α rhythms exist in the small frequency range of 9.5 to 13 Hz, with their amplitudes depending on whether the social coordination is intentional or incidental and whether the tasks are synchronic or diachronic [19]. Both of these interactions would be expected in the SPAN task. Synchronic interactions dominate during the Scenario where information flows multi-directionally across all members of the crew, while during the Debriefing segment only one person generally speaks at a given time (i.e. diachronic interaction). The Scenario-Debriefing differences in NS Entropy in the alpha region might also result from increased / prolonged periods of alpha suppression resulting from the increased task requirements of the Scenario [20]. While decreases in the alpha NS Entropy dominated the NS EEG spectral profile, they seemed less important for distinguishing between high and low resilience teams. This may in part be due to the central role of alpha NS organizations during the taking of 'Rounds' which is a periodic and routine activity. As the subjects studied were candidates in advanced training, they had several years of practice performing the 'Rounds' routines, and at least one of the social coordination markers in the alpha region (right mu) decreases when people memorize routine behaviors of others [19]. The beta region of the EEG spectrum is often linked with motor and pre-motor activity and Mu oscillations which are believed to be part of a human mirror neuron system [21, 13]. Mu oscillations are characterized by an α component of ~8 – 13 Hz attributed to sensory-motor areas (S1 M1), and a beta component of ~15 – 20 Hz which may link to anticipatory motor activity These rhythms are modulated by the direct observation and imagination of movement. Planning, as well as the execution of hand movements desynchronize (i.e. suppress) these rhythms, while inhibition of motor behavior enhances their activity [22, 23]. The neurodynamic organizations of resilient and less resilient teams showed beta region differences during the Scenario with less resilient teams showing significantly ($p < 0.05$) lower NS Entropy levels. These correlations were mainly seen with the CzP0 and F3Cz sensor combinations.

The synchronizations in the γ region are more enigmatic as social coordination markers have not yet been described in this region. In individuals however, α β and γ oscillations interact during working memory manipulations [12]. In this regard it is interesting that periods of γ synchronization were often observed in association with oscillations in α & β bands as well. These periods of increased team neurodynamic organizations in the γ region during the Scenarios were concurrent with 'periods of interest' for the team [5]. This suggests a process whereby a team gradually matched its cognitive organization to changes in the task, and once the team successfully adapted to, or changed the structure of the task, the team developed a new operating rhythm. Neurodynamic measures of the team's rhythm might help evaluators detect when that rhythm is more subtlety disrupted than in the simulation pause above, perhaps enabling a timely instructor intervention, such as real-time coaching, to help the team reorganize cognitively and re-establish its rhythm. A more ambitious aim would be for teams to become self-aware enough to detect these disruptions themselves with behavior clues and to self-correct. Thus, the correlation of NS Entropy levels with related behavior clues is a possible future outcome. Generally, the higher performing teams had fewer periods of decreased NS Entropy (i.e. increased neurodynamic organization) and / or periods of smaller duration or magnitude during the Scenario. This observation was confirmed by correlation analysis between team synchrony and STBT ratings. This fact may complement observer-based measures as a way to quantify the proficiency and resilience of teams; a very useful outcome for developing teams over time in preparation for challenging real-world missions.

What was unexpected from these analyses was the negative correlation between team synchronization and evaluator ratings in the Briefing segment. This relationship suggests that the more cognitively organized a team is during the Briefing, the better they will perform on the task. If larger scale fluctuations indeed relate to the need for increased team organization then by identifying significant periods of team reorganization, instructors could advantageously target discussions and future training activities to develop team skills in these areas, as well as objectively follow team improvement over time. Additionally, a cognitively dis-organized team Brief might provide an early signal to instructors regarding the team's brittleness, and that the team might need more interventions (such as coaching) during the training event.

Neurodynamic measures may also have utility for determining when a team is becoming brittle or 'drifting into danger'. Detection of team breakdowns can be difficult due to the subtle onset and multiplicity of causes before a critical transition towards failure [24]. Team breakdown can be perceived as a sudden event with a dramatic loss of effectiveness, and more often than not, this decrease in performance is a gradual or incremental process [25]. More insight about when teams begin reorganizing would be a step forward toward understanding the antecedent behaviors and developing strategies against them in the future, perhaps in real-time, if teams can be identified as tending toward breakdown.

5 Acknowledgements

This work was supported in part by The Defense Advanced Research Projects Agency under contract number(s) W31P4Q12C0166, and NSF SBIR grants IIP 0822020 and IIP 1215327. The views, opinions, and/or findings contained are those of the authors and should not be interpreted as representing the official views or policies, either expressed or implied, of the Defense Advanced Research Projects Agency or the Department of Defense. **This work was supported by work unit number F1214. JL** is an employee of the U.S. Government. This work was prepared as part of my official duties. Title 17 U.S.C. 105 provides that 'copyright protection under this title is not available for any work of the United States Government.' Title 17 U.S.C. 101 defines U.S. Government work as work prepared by a military service member or employee of the U.S. Government as part of that person's official duties

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