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Intermediate Neurodynamic Representations: A Pathway towards Quantitative Measurements of Teamwork?

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Abstract. We explored the possible linkages between expert observational ratings of team performance and the fluctuating neurodynamics of healthcare and submarine navigation teams while they conducted realistic training in natural settings. Second-by-second symbolic representations were created of team member's electroencephalographic (EEG) power across the 1-40 Hz EEG spectrum, and quantitative estimates of the changing dynamics were calculated from the Shannon entropy of the data streams. Significant correlations were seen between the symbol streams entropy levels and ratings of team performance by observers using TeamSTEPPS® (healthcare), or Submarine Team Behavior Toolkit (submarine teams) rubrics. These results suggest that the frequency, magnitude, and / or durations of the teams' neurodynamic fluctuations might reflect performance aspects detected by expert raters.

INTRODUCTION

Our understanding of how to assemble, train and improve teams' performance has been slowed by a lack of quantitative and objective measures of teamwork. Currently, most evaluations of teams performing natural tasks rely on experts who observe and rate teams across important, but quantitatively vague dimensions like leadership, team structure, and situation monitoring using vetted rubrics. One widely used evaluation comes from the TeamSTEPPS® program which was developed for evaluating teams across healthcare (Baker, Amodeo & Krokos, 2009). A second instrument, the Submarine Team Behavior Toolkit (STBT), focuses on team resilience and was designed for evaluating military teams (Lamb, Lamb, Steed & Stevens, 2014).

Observational / behavioral ratings like TeamSTEPPS® and STBT tend to rely on macro team performance features by summarizing observations over extended periods of time. While the shorter-term dynamics of the team are implicitly acknowledged in the ratings process, the dynamical details are often lost. As a result, the momentary dynamics of teams performing in natural situations have been largely unexplored.

Recent advances in the physiologic and behavioral monitoring of humans are providing new ways of capturing team performance data over short time scales, and are leading to new conceptualizations of teamwork. For instance, changes in the regular pinging of a heart rate monitor may simultaneously trigger similar brain activities in the visual, auditory, and cortical regions of the brains of all team members, i.e., a form of natural synchronization. Such synchronization has been repeatedly seen with subjects viewing movie clips (Hasson, Nir, Levy, Fuhrmann & Malach, 2004), especially when those clips contained emotionally-rich scenes (Nummenmaa, Glerean, Viinikained, Jaaskelainen, Hari & Sams, 2012; Dmochowski, Sajda, Dias & Parra, 2012).

The naturalistic setting of the stimuli in these studies suggests that these ideas of synchrony might be extended to teams performing complex tasks where team members would be neurodynamically entrained to particularly important segments of the task.

Teams differ from individuals viewing a movie in important ways. While task signals may simultaneously arrive to each team member, the information in them may be perceived differently by each member depending on their experiences and responsibilities within the team. Teams can also shape the storyline by being active parts of a coordinated system where each team member influences, and is influenced by the others through social coordination. These social coordination activities lead to the generation of a second set of signals, not from the task or the environment, but from other team members while they try to understand each other.

Conceptually, what is exchanged between teammates during teamwork is information. The information may be packaged in words (Cooke, Gorman & Kiekel, 2008), non-verbal social interactions (Menoret, Varnet, Fargier, et al, 2014) like gestures (Schippers 2010; Caetano, Jousmaki & Hari, 2007), posture (Shockley, Santana & Fowler, 2003), facial expressions (Anders, 2011), and even periods of silence (Gardezi, Lingard, Espin, Whyte, Orser & Baker, 2009), all of which contribute to the overall team dynamics.

It is not surprising that neurophysiologic processes are the underpinnings of the information exchanges in teams, for instance speaker-listener couplings (Stephens, Silbert & Hasson, 2010). Multiple neuromarkers of social coordination have also been described in the 9-12 Hz (or alpha) frequency range (Tognoli & Kelso, 2013). These markers include the 10.9 Hz phi complex which is modulated by intentional coordination (Tognoli, Lagarde, De Guzman & Kelso, 2007), and the medial left and right mu EEG components in the alpha (9 - 11 Hz), and beta (~15 - 20 Hz) frequencies which may represent activities associated with the human mirror neuron system (Oberman, Pineda & Ramachandran, 2007; Pineda, 2008). The mirror neuron system is a collection of neurons that respond to actions we see in others. These neurons are active both when a person executes a motor act and when he observes another individual performing that act (Rizzolatti, Fogassi & Gallese, 2001). Through this system the changing sequence of actions by one person leads to sequences of actions in others; a form of social 'resonance' (Schippers, Roebroeck, Renken, Nanetti & Keysers, 2010).

While these and similar studies reveal the low-level details of social coordination, the impact of these studies on guiding the process and evaluation of teamwork has been minimal. One reason is that the micro level speech, gesture, posture and neurodynamic variables are short-lived and show weak domain or task specificity and cannot be easily linked to the macro-level observations of raters. An approach for extending the usefulness of these short-lived activities for measuring team performance would be to view them as hierarchies of fast and slow variables (Flack, 2012). Slow variables as the name suggests, arise from mechanisms that naturally integrate over faster microscopic dynamics, and represent some average of the noisier activities below. For instance, as neurodynamic hierarchies are transited upward from faster scales to slower scales what would be lost in the mechanistic details of neuronal spike generation and propagation would be gained by tighter relationships with more easily-recognized, observer-defined variables such as team coherence, flexibility or resilience. In this way the more 'intermediate level' representations could provide a meaningful bridge between the milliseconds scales of human brain processing and the observational performance estimates of expert facilitators.

Our hypothesis has been that meaningful intermediate representations might be developed spanning time scales of seconds to minutes that would bridge the fast dynamics of common neurophysiologic markers of social coordination with the slower performance variables that arise from behavioral observations like TeamSTEPPS®. These models could begin to link theory and practice in an understandable way, and be applicable to many different team settings, moreover might serve as objective measures of teamwork.

Several years ago we explored an information / organization-centric approach for quantitatively mapping the neurophysiologic organizations of teams as a way of relating their fluctuating dynamics to team activities, communications and performance (Stevens, Galloway, Wang & Berka, 2011; Stevens & Galloway, 2015). The goal was to develop data streams that had internal structure(s) with temporal information about the present and past organization, function and performance of the teams, and members of the team.

Electroencephalography was chosen for these studies as it provides real-time and high resolution temporal measures in an unobtrusive fashion. EEG is the recording of the brain's electrical activity at different regions along the scalp. The rhythmic patterns in the electrical oscillations from different brain regions contain signals representing complex facets of brain activity, many of which reside in the 1 – 200 Hz frequency range (Buzaki, 2006). Commonly described frequency bands include: 1) Delta (~ 1-5 Hz), often associated with deep sleep, and perhaps a role in the inhibition of sensory stimuli interfering with internal concentration (Harmony, 2013); 2) Theta (~7 Hz), related to the processing of episodic information, predictive navigation, and memory encoding and retrieval (O'Keefe & Dostrovsky, 1971; Battaglia, Sutherland & McNaughton, 2004); 3) Alpha (~10 Hz), the dominant EEG frequency in the awake human brain and while primarily thought of as a marker of visual attention, its significance has expanded to one of attention in general, and perhaps prioritizing visual stimuli (Bonneford & Jensen, 2015; Palva & Palva, 2007); 4) Beta (~20 Hz), reflecting the cognitive control of motor processes and perhaps top-down brain processes in general; and, 5) Gamma (>30 Hz), involved in attention, memory encoding and retrieval and may operate by transmitting temporal sequences of information across brain regions; they are often nested or phase-locked to theta and / or alpha rhythms (Lisman & Jensen, 2013).

Our approach for modeling such dynamics was to create a symbol each second that showed each team member's EEG power levels at individual frequencies in relation to those of other team members. A sequence of such symbols spanning the length of the performance would contain second-by-second neurodynamic history of the team, the resolution of which would depend on the number of frequencies analyzed and the number of EEG channels.

To the extent that the task activities and team member interactions are predictable, the dynamical structure of this history might be relatively smooth. If however, an alarm sounded, all team members might experience similar changes in their alpha rhythms associated with increased attention until they determined the location and cause, and then adjust their balance of rhythms. The similarity in the neurophysiologic processes of the team members would likely alter the temporal structure of the symbolic data streams.

Similarly, if the prediction horizon of individual team members shortened due to the speed of the evolving task in relation to their experience, uncertainties may develop in their shared understandings leading to changes in their dynamical flow as the team regroups. The most interesting segments in these data streams, i.e. those with the most structure, might be those associated with acute or chronic changes to the team / task and where a subset of closely-related symbols would persist for minutes or more. The questions posed for this study were whether we could detect these persistent neurodynamic structures, and whether the frequency, magnitude, and / or duration of these segments could be linked to expert estimates of team performance.

METHODS

These studies were conducted with two sets of teams performing two different simulation tasks. Both simulations contained a Briefing where the goals of the simulation were presented, a Scenario segment which was the dynamic and evolving task, and a Debriefing which was an open discussion of what worked, including long and short term lessons.

The goal of the first task was for US Navy Submarine Navigation (SPAN) teams to safely pilot a simulated submarine into or out of port; these were required exercises as part of standard training at the US Navy Submarine School. There were five persons per team and seven teams were studied who met the criteria of 1) having two independent evaluators performing ratings using the STBT rubric, 2) EEG from the complete performance (i.e. the Briefing, Scenario and Debriefing segments) was available for modeling, and, 3) each of the training segments was at least 300 seconds long.

The second set of tasks were operating room simulations where the core construct was ventilation management. There were six three-person teams who participated and the teams consisted of either fourth year-medical students or experienced operating room staff. All studies were submitted to, and approved by the appropriate institutional review boards.

Electroencephalography

The X-10 wireless headsets from Advanced Brain Monitoring, Inc. were 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 according to the international 10-20 system; bipolar derivations were included which have been reported to reflect sensorimotor activity (FzC3) (Wang, Hong, Gao & Gao, 2007), workload (F3Cz, C3C4) (Roux & Uhlhaas, 2014) and alpha wave components of the human mirror neuron system (Oberman et al, 2007). 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 (Levindowski, Berka, Olmstead, et al, 2001). These interpolations represented <5% of the data and in previous studies have not significantly influenced the detection of team neurophysiologic activities which occurred throughout the performances (Stevens & Galloway, 2014; Stevens, Galloway, Wang, et al, 2012). The EEG power was computed each second at each sensor for the 1 – 40 Hz bins.

Neurodynamic Modeling

We illustrate the generation of Neurodynamic Symbols (NS) for three-person healthcare teams; similar procedures were used for the five-person submarine teams. Each second the power levels of one of the forty EEG frequency bins (i.e. 39 Hz) of a team member was equated with his/her own average levels over the task. This identified whether at this time an individual team member was experiencing above or below average EEG power at that frequency and whether the team as a whole was experiencing above or below levels.

In this process the EEG power levels were partitioned into the upper 33%, the lower 33% and the middle 33%, which were assigned values of 3, -1, and 1 respectively, values chosen for data visualization purposes (Stevens & Galloway, 2014). The next step combined these values at each second for each team member into a three-element vector which was then assembled into a symbol (Fig. 1A). The three histograms in this symbol indicate that at this second the registered nurse (RN) had below average EEG levels, the scrub tech nurse (ST) had above average and the anesthesiologist (AN) had average levels. Figure 1B shows the complete symbolic state space when each second of the performance was processed. Each NS situated the EEG power levels of each team member in the context of the levels of the other team members, and when the second-by-second symbols were aligned the data stream contained a history of the team's neurodynamics.

A quantitative readout of this history was generated by calculating the Shannon entropy (Shannon, 1951) of the symbol distribution over a 60s moving window. Performance segments with restricted symbol expression had lower entropy levels which is thought to reflect rigidity, while segments with greater symbol diversity had higher entropy which is thought to reflect neurodynamic flexibility.

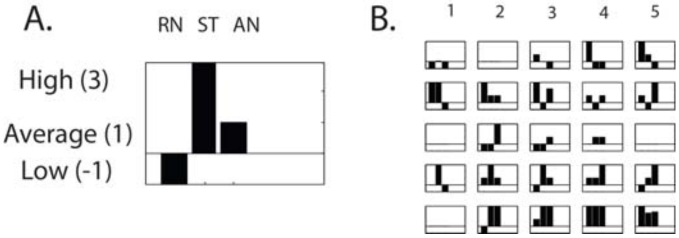

Figure 1. Neurodynamic symbols and symbol space. A) Sample neurodynamic symbol showing the power levels of three team members. B) The 21 symbol state space is shown that was used when creating the neurodynamic symbol data stream for entropy calculations. RN = Registered Nurse; ST = Scrub Tech Nurse; AN = Anesthesiologist.

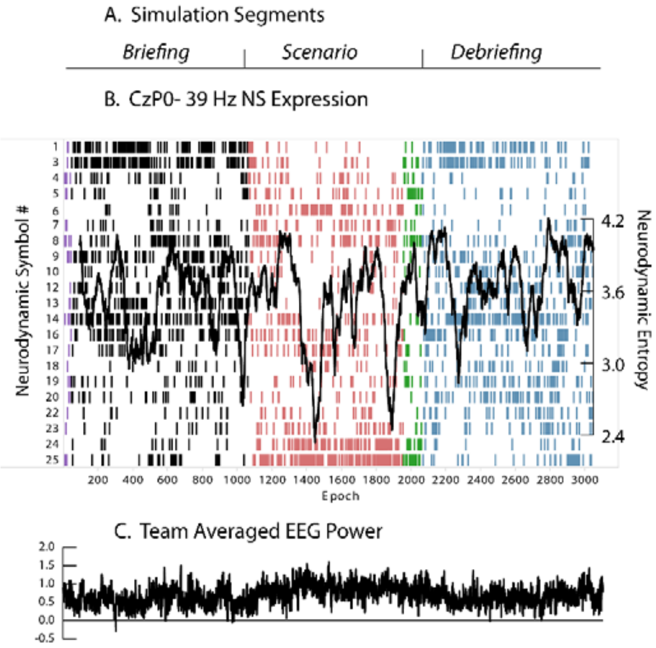

Figure 2. Team neurodynamics for a healthcare performance. A) Markers highlight the simulation segments. B) Each second the NS symbol being expressed in the 39 Hz data stream from the CzP0 sensor was marked next to the NS symbol. C) This figure plots the 39 Hz average raw EEG power for the three person team. The line trace overlaying Fig. 2B shows the Shannon entropy values.

As tasks evolved through the major simulation segments and momentary performance shifts, the distributions of NS changed, and by plotting the time ordered neurodynamic symbols the changing neurodynamics could be reconstructed and visualized (Fig. 2). One consistent feature was the change in NS distributions at the task segment junctions. The major shift in the 39 Hz EEG frequency was from the team expressing high gamma band power in the Scenario (NS 24 & 25 in Fig. 1B) to lower levels in the Debriefing (NS 1 & 3 in Fig. 1B). These changing Scenario – Debrief dynamics are typical of what we have seen with military tasks (Stevens, Gorman, Amazeen, Likens & Galloway, 2013; Stevens et al., 2011). The rapidity of these changes (seconds) indicates that NS expression is highly sensitive to the team experiences and changes in the task environment.

A second NS expression feature was that symbol distributions were not uniform, but were characterized by segments where a limited subset of the symbols persisted (around 1400s for instance). Estimates of the degree of NS persistence were quantitated by calculating the Shannon entropy of the NS stream (Stevens & Galloway, 2015).

A three-dimensional time *x* frequency *x* entropy topological map of this performance over the 1-40 Hz EEG spectrum of the CzP0 channel (Fig. 3) showed that performance segments with low NS entropy were spaced throughout the performance and primarily distributed across the 8-10 Hz and 30-40 Hz regions.

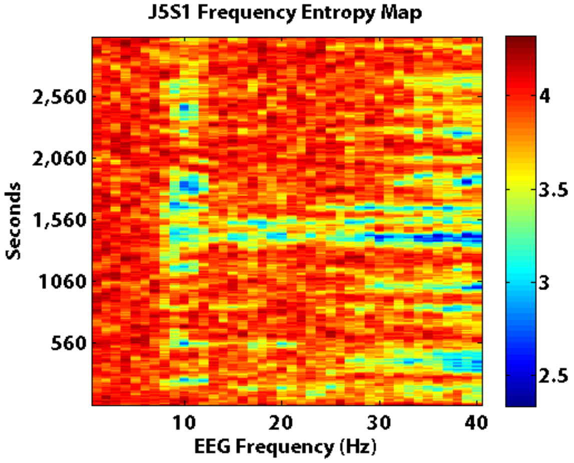

Figure 3. Sample neurodynamic entropy topology map generated from the 1-40 Hz frequency bins of the CzP0 sensor. This map plots the NS entropy levels as a function of performance time and EEG frequency.

Linking Neurodynamics with Team Proficiency Ratings

The correlation between STBT observer ratings and the neurodynamic entropy of the entire performance (i.e. the Brief, Scenario and Debrief segments) was not significant (*r* = -.28, p = .53). Correlations were repeated after separating the performance into 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.

During the Briefing, there was a significant negative correlation (*r* = -.81, p < 0.005) between the NS entropy and the STBT ratings indicating that the more resilient teams were neurodynamically more organized than the less resilient teams. During the Scenario (Fig. 4A) there was a positive correlation between STBT ratings and NS entropy (*r* = .43, p = .04) indicating that highly resilient teams were neurodynamically less organized than the less resilient teams. During the debriefing, the correlation was again negative (r = -.36, p = .03). The negative correlation means that high STBT rating scores were most highly correlated with low NS entropy levels, i.e. more synchronized and organized teams. Positive correlations mean that higher performance was correlated with less neurodynamic synchrony / organization.

Correlations between NS entropy and TeamSTEPPS® ratings were also performed for the healthcare teams. A positive correlation was again seen between observer ratings and neurodynamic entropy in the Scenario (Fig. 4B).

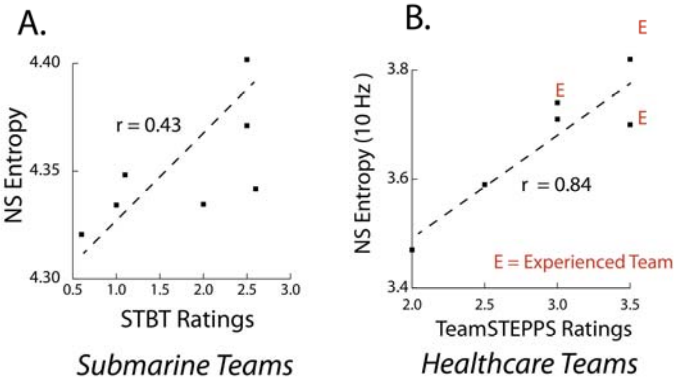

Figure 4 Correlations between NS entropy and observer ratings for A) submarine piloting and navigation teams and B) operating room teams. Both figures plot the Scenario data.

DISCUSSION

In this study we have shown that neurodynamic symbols composed of the team member's EEG power might serve as a useful intermediate representation for linking micro and macro – team activities. By using the symbol lookup table in Fig 1B, the regions of interest in the symbolic data streams can be decomposed into either trends of individual team members EEG power or into a deeper understanding of the composition and fluctuations in the raw EEG power in the context of the changing task activities. Only a quick glance at Fig. 2B is needed to understand the changes in gamma power associated with the major task segments. While similar inter-segment trends can be gleaned from the average EEG power profile (Fig 2C), the symbolic maps were more revealing of intra-segment changes like those occurring in the Scenario between 1350 – 1500 associated with an unsuccessful intubation, or in the Briefing between 300 – 500s which resulted in the appearance of a new team re-organization (NS #8) in preparation for the Scenario.

At higher levels the correlations between NS entropy levels and team performance indicates that some features of expert ratings are also incorporated into the models. In the future the models can be extended to derive more details about what is being measured by raters, by performing correlations with the sub-dimensions of both TeamSTEPPS® (team structure, leadership, situation monitoring, mutual support & communication) and STBT (dialogue, decision making, critical thinking, bench strength & problem solving capacity).

This intermediate representation is not without limitations, as it is uncertain what exactly is being measured cognitively. To some extent this is not surprising as details of teaming are poorly understood in the tens of seconds to extended minutes time scale. The similarities in both dynamics and correlations with observations suggests that the underlying construct might be general to certain types of teamwork. A better understanding of these meanings can be approached by performing correlations with different frequency bands, sensor locations or spatially independent components (Onton, Westerfield, Townsend & Maekig, 2006).

Finally, collapsing the team into a single data stream simplifies linking neurodynamic measures with other data streams of team performance (speech, gestures, etc.). In this way Gorman, Martin, Dunbar, Stevens, Galloway Amazeen & Likens (2015) have shown novice / expert differences in the correlational time lags between team neurodynamics and team speech.

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