Team Neurodynamics
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# Teams Reorganize Neurodynamically When They Sense Loss of Control

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**Abstract.** Perturbations to the normal flow of teamwork arise externally through changes in the environment or internally as a result of the team's processes / decisions. We used quantitative neurophysiologic models of the rhythms and organizations of teams to examine the effects of these two classes of perturbations on team neurodynamics. Electroencephalographic (EEG) signals from dyads were transformed into cognitive workload estimates and then into neurodynamic symbols (NS) showing the second-by-second workload of each individual as well as the team. Periods of changing cognitive organizations were identified by a moving average smoothing of the Shannon entropy of the NS data stream and related to team speech, actions and responses to external and internal task changes. Dyads performing an unscripted map navigation (HCRC Map Task) developed fluctuating NS dynamics around the construct of workload which were disrupted by external task perturbations or when the team became confused or uncertain of their progress. Importantly, we detected no significant neurodynamic fluctuations associated with periods when the team made mistakes and did not realize they made the mistake. These results indicated that neurodynamics reorganizations occurred in teams in response to multiple types of perturbations, but primarily when the team perceived difficulties.

**Keywords:** team neurodynamics, entropy, coordination dynamics, rhythms

## 1 Introduction

Teams are a social response to a recurring, and often required, task that is too complex for an individual to accomplish. The repetitive nature of most tasks leads to the assembling of teams with members having the skills to manage internal and external challenges that have the potential to disrupt the system [1]. Complex systems are always changing however, due either to external interactions with other complex systems (e.g. the environment or other teams) or as a result of internal changes that the team makes itself through their prior activities and / or decisions. External disrup-

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tions are often the result of changes in the environmental context of the task. These disruptions require responses outside the team's normal performance envelope and test their capacity to adapt to changes without a fundamental breakdown, i.e. their resilience [2]. If the disruptors are internal, additional safeguards or quality checks can be implemented at the team level that would prevent re-occurrence of the errors. The transient organizational changes that teams undergo when encountering internal or external disruptions are poorly understood, in part due to the temporal insensitivity of most quantitative measures of teamwork.

We have been developing a neurophysiologic platform for studying teams and their responses to perturbations. Our work has focused on constructing an information and organization-centric team neurodynamics framework that is information centric in the sense that raw EEG measures from each team member are combined into symbols showing the levels of different cognitive measures of each team member and the team as a whole [3, 4, 5]. These neurodynamic symbol streams (NS) are probed for regions containing information related to team performance much in the way that words in a sentence or the codons in nucleic acids convey information. Importantly, fluctuations in the mix of symbols identify 'interesting periods' of team organization and the frequency, duration, and magnitude of these fluctuations can be quantified by measuring the Shannon entropy of the data stream [6, 7].

The purpose of this study was to investigate a teaming situation where both external and internal disruptions were likely to occur to determine if there was a differential sensitivity of neurodynamics responses to the two types of disruptions. Our hypothesis was that both disruptions would result in the cognitive reorganization of teams and that external disruptions, due to their unexpected nature, would result in larger reorganizations than those induced by internal disruptions.

## 2 Methods

### 2.1 Participants and Task

The subjects for this task were seventeen 11th and 12th grade student teams who were recruited from Advanced Placement Chemistry classes. Informed consent was obtained from the parents allowing the students to participate in the study and to have their images and speech made available for additional study. The task used was based on the Edinburgh Map Task (MT) [8]. One person, the instruction giver (Giver, abbreviated **G**), had a map with a path on the computer screen map (Fig. 1A) and attempted to verbally guide the other person, the instruction follower (Follower, abbreviated **F**) in drawing that path on the Follower's map (Fig. 1B). The resulting dialog was unscripted and contained easily identified short-term goals. The task was not timed and the participants received no feedback on the quality of their performance.

To support the collection of video and audio streams, the drawing by the Follower was performed on a computer using Adobe Acrobat standard drawing and erasing tools. The Giver and the Follower were fitted with a 9-electrode EEG unit (Advanced Brain Monitoring, Inc., described below) and seated in front of a computer configured with Morae Software (Techsmith, Inc.) which simultaneously logged EEG, audio, video, and the Follower's mouse clicks. This configuration supported the temporal alignment of speech, mouse movements and neurophysiologic measures.

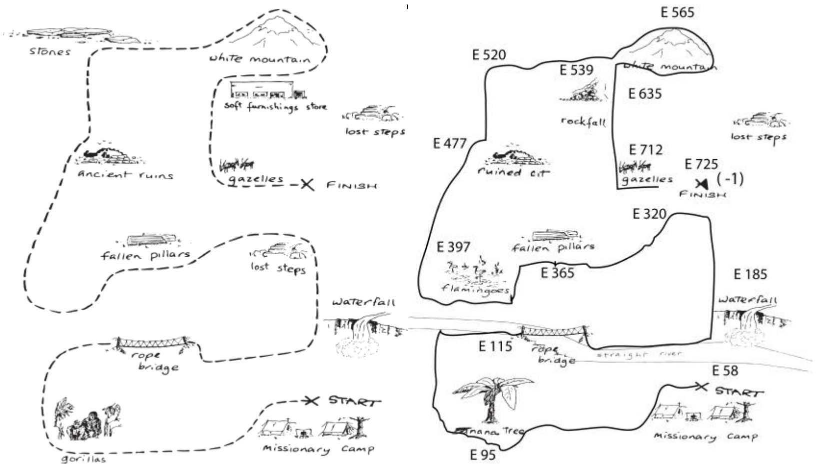


**Fig. 1.** A Comparison of a Giver's (left) and Follower's (right) Maps. The dotted line on the Giver's map shows the desired path, and the solid line on the Follower's map shows what was drawn during performance G2S1. The numbers indicate the approximate epoch (second) of the performance. The numbers in parentheses indicate the points deducted for missed marks.

A sample performance is shown in Fig. 1 with the dotted line on the Giver's map (left) showing the intended path. There were two map positions which had different landmarks; 1) on the lower left the Giver had Gorillas and the Follower had Banana Trees, and, 2) the Giver's Ancient Ruins icon was labeled Ancient City on the Followers Map.

There were also multiple points where the teams could get off track due to similarities or duplications of the landmarks. One example was where the Giver had two icons for Lost Steps, one in the center and one in the upper right while the Follower had only one in the upper right. This became a source of confusion for some teams like those in Fig. 2. Here, the performance showed a deviation after the Waterfall toward the Lost Steps icon positioned on the Follower's map. A second example was where the Giver's map had the landmark Stones in the upper left corner while the Follower's map had a Rock Fall landmark toward the center of the map. This was a point of confusion for the team in Fig. 2A; between epochs (E) 415 to 421 the dialogue was "(**G**) and then you will see the Stones", "(**F**) the Rock Falls? "(**G**) ya", Just go….", "(**F**) So then I go around and then….". The Follower then proceeded to deviate to the right (E 442) and go around the Rock Fall. Examination of the team dialogues showed that a common feature of these mistakes was making assumptions about other person's speech, i.e. lack of error checking.

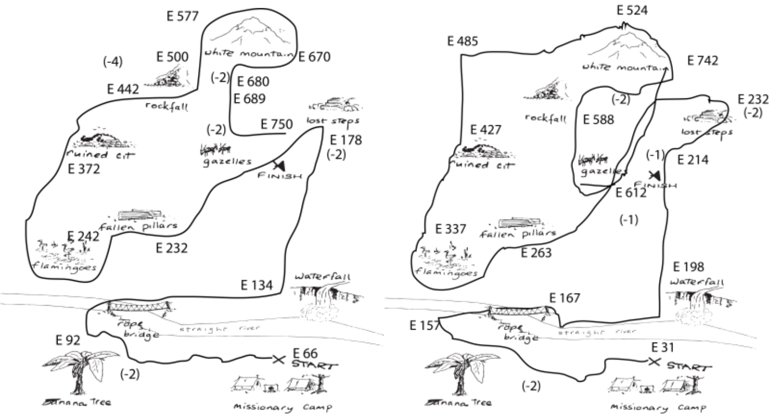


**Fig. 2.** Two Low-Scoring Map Task Performances. This figure shows the Follower's trace from two performances of the task shown in Fig. 1. The numbers indicate the approximate epoch of the performance. The numbers in parentheses indicate the points deducted for missed marks. *Left*, performance G4S1, *Right*, performance G3S1.

A scoring system was used to rate the performances with points deducted for drawing inaccuracies. In this system a Bad Miss, where the route went on the wrong side of a marker, was scored -2 while a Good Miss where the edge of a feature was clipped or if the route was taken too widely (i.e. > ½ the height of a feature) was scored -1. The performance in Fig. 1B was highly rated with a single point being deducted for not extending the line to the Finish. The two performances in Fig. 2 were among the lowest scored in the MT data set.

## 2.2 Electroencephalography (EEG)

The B-Alert® system by Advanced Brain Monitoring, Inc. contains an easily-applied wireless EEG system that includes software for identifying and eliminating multiple sources of biological and environmental contamination. It allows second-by-second classification of cognitive state changes [9]. TheB-Alert® Model 600B 9-channel wireless headset includes sensor site locations: F3, F4, C3, C4, P3, P4, Fz, Cz, POz in a monopolar configuration referenced to linked mastoids. B-Alert® software acquires the data and quantifies engagement (EEG-E) and mental workload (EEG-WL) in real-time using linear and quadratic discriminant function analyses with model-selected PSD variables in each of the 1-hz bins from 1 – 40 Hz, ratios of power bins.

## 2.3 Team Neurodynamics

For studying team processes, we chose a symbolic approach for combining the data rather than directly using two concurrent EEG data streams; this lets the current status of the team as a whole to be represented by a single symbol. To generate these symbols we equated the absolute levels of EEG-WL of each team member with his/her own average levels over the period of the particular task. This enabled the identification of whether a team member was experiencing above or below average levels of EEG-WL and whether the team as a whole was experiencing above or below average levels. As previously described [3-5] in this normalization the EEG-WL levels were partitioned into the upper, lower, and middle thirds; these divisions were assigned values of 3, -1, and 1 respectively, values that were chosen to enhance symbol visualizations. For instance, the symbol in Fig. 3A shows a situation where the EEG-WL of **G** was high and that of **F** was low; in the text this is represented as $\mathbf{G^h}$ $\mathbf{F^l}$.

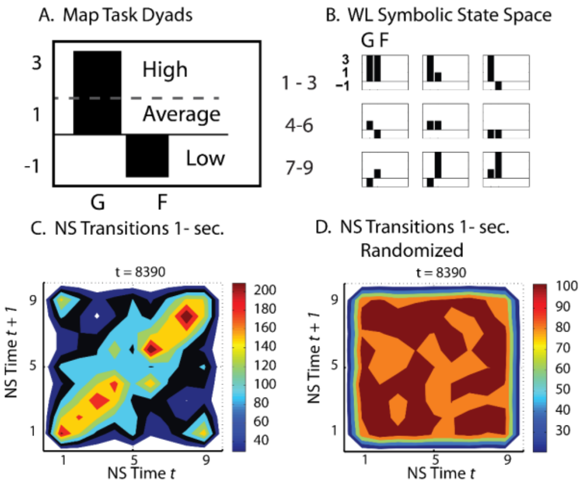


**Fig. 3.** Structural Properties of Neurodynamic Symbol Streams. A) Levels of EEG-WL were extracted from raw EEG signals and partitioned into high, average and low categories (G = Giver, F = Follower). B) An ANN generated nine-symbol state space map shows the possible combination of EEG-WL levels. C) The transition frequencies are shown from the time *t* symbol number (x-axis) to the time *t + 1* second symbol number (y-axis). D) The symbol stream in (C) was randomized before creating the transition map.

The next step assembled the second by second values for each team member into a vector representing the state of EEG-WL for the team as a whole; these vectors were used to train artificial neural networks (ANN) to classify the state of the team at each second. In this process the second-by-second normalized values of team EEG-WL for a performance (or multiple performances when across team models were being generated) were repeatedly (50-2000 times) presented to a 1 x 9 node unsupervised ANN. The result of this training was a series of patterns called Neurodynamic Symbols (NS) that show the relative levels of EEG-WL for each team member.

During the training process a topology developed whereby similar EEG-WL vectors become adjacent through short-range excitatory interconnections while the more disparate vectors are inhibited and co-locate further away. The output of the ANN training is a symbolic state space showing the possible combinations of EEG-WL across members of the team for a performance. The resulting ANN topology for these studies is shown in Fig. 3B where NS #1 (upper left corner) depicts a time where both **G** and **F** expressed above average levels of EEG-WL (i.e. $\mathbf{G^h}$ $\mathbf{F^h}$). In NS #2 & #3 the

EEG-WL expression of **F** decreased and at NS #6 the NS represented the state $\mathbf{G}^{l}$ $\mathbf{F}^{l}$. This topology helps interpret the structure and dynamics of NS data streams, particularly when teams with more than two members are involved. The primary data source for further analysis was the second-by-second sequence of NS symbols.

One goal was to develop neurodynamic measures that had structures conveying information about the organization, function and performance of teams. Structure hererefers to a pattern of relationships among entities, in our case, a series of symbols representing the neurodynamic state of the team, around a construct like EEG-WL. The short-term structure in the neurodynamic data streams of the entire MT dataset (8980 epochs) is shown in Figure 3C. This transition diagram plots the NS being expressed at time *t* vs. that expressed one second later (i.e. $t + 1$). The non-random arrangement of the NS in the data stream is seen by comparing this figure with one where the NS data stream was randomized prior to plotting the transitions (Fig. 3D). The NS data structure was highlighted by the diagonal suggesting a short-term persistent component. The thickness of the diagonal indicates there were also transitions from NS to their immediate neighbors on the linear ANN topology map. The transitions on the diagonal were also expressed at different frequencies with the NS #8 – NS #8 transition being particularly frequent while the NS #5 – NS #5 transitions were less common. Thus within the data stream some NS repeats were more common than others and these differences may have significance (i.e. information) regarding the performance. Fluctuations in the mix of symbols in the second-by-second data stream were then used to identify this information within the performances.

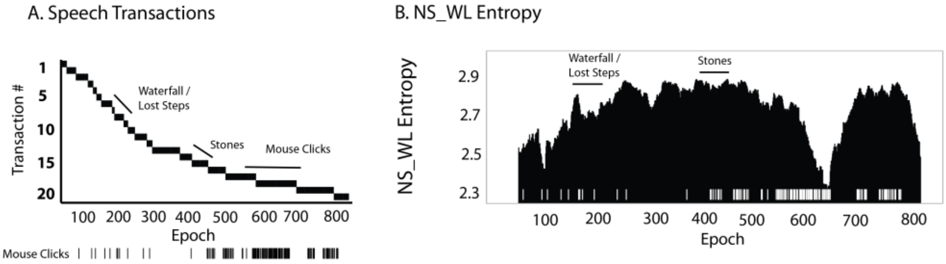
Fluctuations in the organizational state of the teams were detected and quantified by measuring the Shannon entropy [6,7] of the symbol stream over a sliding history window where the entropy was first measured over the initial 70 sec. Then at subsequent seconds the window was shifted removing the first symbol and appending a new one at the end; the entropy was then re-calculated. In this context, if a segment of the data stream had a random mix of 9 NS the entropy would be 3.17, while if the symbol number in this data stream was restricted to only 5 of the 9 (i.e. more symbol persistence or organization), the NS Entropy level would drop to 2.32. The entropy values themselves provide no information on the nature of the organization, only that there was greater or lesser organization. The organizational specifics of these segments however can be deduced from the symbolic state space maps like those in Fig. 3B.

## 3 Results

Most Map Task performances showed changing NS_WL Entropy dynamics when the Follower experienced difficulty drawing with the mouse which resulted in a large number of mouse clicks. Most of the mouse click errors were because they touched a previously drawn portion when beginning a new transaction. Clicking the pencil and beginning to draw alleviated the problem. This external change in the task was an unintended consequence of having the Followers draw their paths on a computer. The effects these disruptions had on speech and team neurodynamics are shown in Fig.

4A, which plots the times of the team's speech transactions; the corresponding trace for this performance is in Fig. 2A.

Speech transactions are defined as sub-dialogues that accomplish one major step in the plan for drawing the trace. A typical transaction gets the Follower to draw one route segment on the map. For instance, the phrases "(**G**) After you go through it (Rope Bridge) you are going to see a Waterfall on the Right. (**F**) So like I go straight to.., (**G**) Ya straight again to the Waterfall. (**F**) Is…is there like straight like flat? (**G**) Yeah, straight and then don't go around. (**F**) Alright."


A. Speech Transactions

B. NS_WL Entropy

**Fig. 4.** Linking Speech Transactions and NS_WL Entropy Dynamics with Mouse-Click Events. Figure 4A plots the time for each transaction (solid blocks) and below this are the individual mouse clicks used by **F** when drawing. Fig. 4B shows the NS_WL entropy profile. The times of the Waterfall-Lost Steps and Ancient Ruins–Stones segments are labeled on each figure.

Early transactions were short (< 20 seconds) and seemingly effective as indicated by the few mouse clicks. Between epochs 135 – 175 the team navigated the Waterfall – Lost Steps segment which as shown in Fig. 2A was the incorrect Lost Steps icon. The speech transaction during this period was similar in length to those immediately before and those after (Fig. 4A). Similarly, there was no drop in the NS_WL entropy levels during this time (Fig. 4B), and the team continued to establish its working rhythm [5]. Between epochs 415 – 462 they navigated the Ancient City – Stones segment, and as the trace shows in Fig. 2A they mistook the Rock Fall landmark for the Stones landmark and traced an incorrect path. Again, there were no discernable changes in either the speech transaction or NS_WL Entropy dynamics. Around epoch 500 the transactions became longer and this coincided with an increased number of mouse clicks. In parallel the levels of NS_WL Entropy began to drop and did not begin to rise until the drawing difficulties ended (Fig. 4B).

The changing speech and neuro-dynamics with drawing problems were expected from previous studies [5], but the absence of these changes when mistakes were made was not. This suggested that either making errors had no effect on speech transaction times or neurodynamic entropy or alternatively the team did not realize their mistakes.

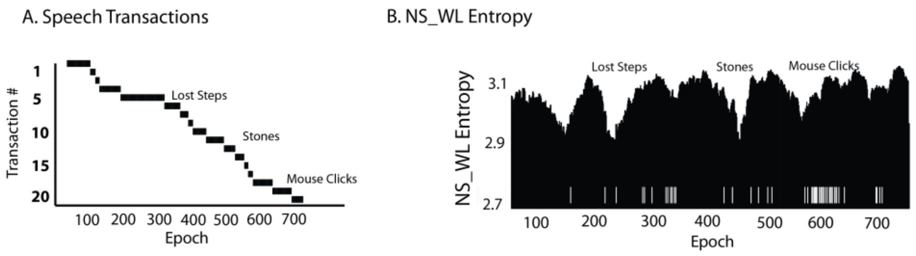
We explored these alternatives by comparing these metrics during similar periods with teams that did not miss the Waterfall – Lost Steps segment. The idea was that the teams that recognized this potential for confusion with the two Lost Steps icons, may spend more time and effort discussing that segment than the teams that did not draw the correct line. This would be evidenced by 1) longer transaction times for this segment compared with the average transaction time and 2) a higher frequency of the terms Waterfall and Lost Steps in the dialogues.

Table 1 shows the transaction times for two teams who missed the correct landmark and two that did not. The transaction time for the incorrect landmark segment approximated that of the average transaction time; i.e there seemed nothing special about that segment. The transactions for the teams that completed the correct segment spent three times longer than the average transaction times. Furthermore, word frequency counts indicated the the terms Waterfall and Lost Steps were used more frequently by those who completed this segment than those who missed this segment (0.4 times / 100 epochs vs. 0.3 times per epoch, ( $\chi^2 = 24.1$, $df = 13$, $p = 0.03$).

| Team | Average | Lost Steps | Missed? |
|---|---|---|---|
| G4S1 | 40.4 | 41 | Yes |
| G3S1 | 49.5 | 42 | Yes |
| G2S1 | 42.8 | 130 | No |
| G1S1 | 80.4 | 309 | No |

**Table 1.** Comparison of the Average Transaction Times with the Waterfall to Lost Steps Transaction.

This increased emphasis of the successful teams on the Waterfall – Lost Steps segment is shown in Fig. 5. There was both an increased transaction time as well as a NS_WL entropy decline, suggesting a major team reorganization as they recognized and resolved this potential difficulty. Similar trends were seen for the period when the team navigated the Ancient City – Stone segment.


A. Speech Transactions

B. NS_WL Entropy

**Fig. 5.** Linking Speech Transactions and NS_WL Entropy Dynamics with Performance events. Figure 5A plots the time for each transaction with several segments labeled. Fig. 5B shows the NS_WL entropy profile and the associated mouse clicks.

## 4 Discussion

Team neurodynamics is an information-organization approach for identifying periods where teams undergo reorganizations with reference to EEG-defined cognitive markers. It is information-centric in the sense that data streams of symbols representing both the activities of teams as well as team members are used to capture overall dynamics, and organization centric in the sense that fluctuations in the entropy levels across the symbols in these data streams reveal interesting periods of team organizations. It is an approach that has proven valuable for studying teamwork in settings as diverse as high school problem solving through required military training scenarios, as neurodynamics reorganizations consistently occur with major changes in the task, and more subtly with disruptions involving stress or uncertainty [3-5, 10]. Our goal for this study was to determine if external disruptions (i.e. out of the team's control) induced similar neurodynamic reorganizations as did internal disruptions.

To study this question in the context of real-world tasks we chose a simplified team – navigation task setting where both forms of disruptions were expected to occur. As we have reported, external disruptions in the form of mouse drawing difficulties had a major effect on the team's reorganization resulting in significant increases in transaction times and large drops in NS_WL entropy. These reorganizations resulted in a nearly 50% decrease in the use of available NS_WL cognitive states from 9 (i.e. NS_WL Entropy = 3.1) to as low as 4 (i.e. NS_WL Entropy = 2.32).

There were also major effects of the internal disruptions, but not necessarily what was expected. Our original idea was that when teams made major path deviations these errors would be reflected in neurodynamic reorganizations. Instead, the teams who made these mistakes seemed not to notice as there were no changes in: 1) the speech transaction times; 2) the dialogues; or 3) in neurodynamic measures. This suggests that they did not recognize the potential for a mistake or realize they made a mistake. In contrast, the teams that successfully completed the traces around these landmarks recognized the potential for error and had extended discussions before cautiously completed the traces. This resulted in both increased speech transaction times as well as decreased NS_WL entropy dynamics during these periods.

Thus when teams perceive they are being effective (whether correctly or incorrectly), the need for cognitive reorganizations is minimal; they are in control. Some teams like achieve this effectiveness by being thorough. Team G1S1 for example was a very effective team with the second highest score of the dataset, but they achieved this effectiveness by sacrificing efficiency with nearly twice the average transaction times of other teams. This suggests that the MT may be a useful platform for studying the optimization of teams where time constraints can be used to study the subtle cognitive reorganizational changes as teams balance the needs of efficiency and effectiveness.

Finally, while we found no evidence for neurodynamic recognition of mistakes unless they were explicitly noted by the team, that is is not to say that EEG signals other than

EEG-WL or EEG-E may exist that signify more implicit recognition of mistakes in a manner analogous to human decision making (11).

## 5 Acknowledgements

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## 6 References

1. Salas, E., Cook, N. J., Rosen, M. A. (2008). On teams, teamwork, and team performance: Discoveries and developments. *Human Factors: The Journal of the Human Factors and Ergonomics Society* Vol. 50 (3): 540-547.
2. Hollnagel, E., Woods, D.D., and Levinson, N. (Eds). (2006) *Resilience engineering: concepts and precepts.* Ashgate, Burlington, VT.
3. Stevens, R.H., Gorman, J.C., Amazeen, P., Likens, A., and Galloway, T. (2013). The organizational dynamics of teams. *Nonlinear Dynamics, Psychology and Life Sciences 17, No. 1, pp. 67-86.*
4. Stevens, R.H., Galloway, T., Wang, P., and Berka, C. (2012). Cognitive neurophysiologic synchronies: What can they contribute to the study of teamwork? *Human Factors* 54, 489-502.
5. Stevens, R. H., and Galloway, T. (2014). Toward a quantitative description of the neurodynamics organizations of teams. Social Neuroscience, *in press.*
6. Shannon, C., & Weaver, W. (1949). *The mathematical theory of communication.* Urbana: University of Illinois Press.
7. Stevens, R. H. (2012). Charting neurodynamics eddies in the temporal flows of teamwork. In *Proceedings of the Human Factors and Ergonomics Society 56th Annual Meeting.* Doherty-Sneddon, G., Anderson, A.; O'Malley, C.; Langton, S.; Garrod, S.; Bruce, V. (1997) Face-to-face and video-mediated communication: A comparison of dialogue structure and task performance. Journal of Experimental Psychology: Applied, Vol. 3(2), 105-125. doi: 10.1037/1076-898X.3.2.105.
8. Berka, C., Levendowski, D. J., Cvetinovic, M. M., Petrovic, M. M., Davis G. et al. (2004). Real-Time analysis of EEG indexes of alertness, cognition, and memory acquired with a wireless EEG headset. *International Journal of Human-Computer Interaction.* Lawrence Erlbaum Associates, Inc. 17 (2), 151-170.
9. Stevens, R., Galloway, T., Wang, P., Berka, C., Tan, V., Wohlgemuth, T., Lamb, J., Buckles, R.: Modeling the Neurodynamic Complexity of Submarine Navigation Teams. (2012). Comput Math Organ Theory DOI 10.1007/s10588-012-9135-9.
10. Libet, Benjamin (1985). "Unconscious cerebral initiative and the role of conscious will in voluntary action". *The Behavioral and Brain Sciences* **8**: 529–566. Retrieved 18 December 2013.