Soft, Embeddable, Dry EEG Sensors for Real World Applications

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Abstract. Over the last decade, numerous papers have presented the use of dry electrodes capable of acquiring electroencephalogram (EEG) signals through hair. A few of these dry electrode prototypes have even progressed from lab-based EEG acquisition to commercial sales. While the field has improved rapidly as of late, most dry electrodes share a number of shortcomings that limit their potential real world applications including: 1) multiple rigid prongs that require sustained pressure to penetrate hair and maintain solid scalp contact, creating higher levels of discomfort when compared to standard wet sensors; 2) cumbersome or chin-strap-type applications for maintaining electrode contact, creating barriers to end user acceptance; 3) rigid active electrodes to compensate for high input impedances that limit flexibility and placement of sensors; 4) inability to safely imbed sensors under protective headgear, restricting use in some fields where EEG metrics are most desired; and 5) expensive sensor manufacturing that drives costs high for use across subjects. Under a recent DARPA Phase 3 contract, Advanced Brain Monitoring has developed a novel semi-dry sensor that addresses the current dry electrode shortcomings, opening up the door for new real world applications without compromising subject safety or comfort. The semi-dry sensor prototype was tested during a live performance requirement at the end of Phase 3, and successfully acquired EEG across all subject hair types over a 3 day testing period. The results from the performance requirement and subsequent results for new advancements to the prototype are presented here.

Keywords: Electroencephalograms (EEG), dry-electrodes, wearable EEG, BCI, Real World Applications.

1 Introduction

While Electroencephalography (EEG) has been used for decades to record the electrical activity of the brain [1] and validated for use in a wide range of applications it has rarely left the controlled confines of the laboratory. Use of medical-grade EEG in real world settings has often been limited by its susceptibility to environmental noise, usability constraints, and availability of technical personnel. Over the last twenty years, however, technological advances have begun to address these issues, enabling medical grade, real world wearable systems.

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The "Holy Grail" for EEG is a self-applied, wearable system that can reliably record medical grade EEG on users in the real world. In the quest for this ideal system, the notion of a “Dry EEG Sensor” has become a popular buzz word, and (in some cases) a de facto requirement. This trend can be explained in part by the unfavorable way in which most dry sensor publications portray "wet" sensor technologies [2-7], particularly as it pertains to Brain Computer Interface (BCI) platforms. The bulk of dry sensor publications use older EEG systems that have since been updated or superseded as their examples of "current" wet EEG platforms. This perpetuates the misconception that the only wet sensor systems available require substantial time to set up each sensor site, depend upon extensive skin preparation (below 5kΩ), are not wearable, are susceptible to electromagnetic interference due to leads from the head to the amplifier, and result in severe discomfort to the user [2-3]. Some combination of these qualities are often listed as shortcomings of existing wet sensors, and thereby benefits of implementing dry sensors. Dry sensor publications often further emphasize their advantage by overstating the amount of residue left behind by wet sensors. These publications rarely acknowledge the existing available medical grade wet sensors that are multi-site systems with short set up times, minimal or zero skin preparation, easily attainable impedances below 80kΩ, wearability for multiple days (during both wake and sleep), low electromagnetic interference in wireless mode and/or storage directly to the device, and high levels of user comfort [8-11]. One remaining, frequently cited, drawback specific to wet sensors is the residue left behind. As aforementioned, dry electrode publications commonly reference wet systems that use 10/20 paste and collodian, and require an experienced laboratory technician for application. In reality, some current wet systems have already eliminated any residues, and for many other applications the residue is minimal and unnoticeable. Moreover, depending on intended use, many wet sensor systems can be self-applied by the end user without any technical personnel required [12-13], and those applications requiring assistance can easily be completed by non-technical personnel.

What remains as a significant drawback for wet sensors when compared against dry sensors is the ability to record long acquisitions (i.e., over 8 hours) without requiring the addition of more gel or paste. This dry sensor benefit should, however, be considered alongside the negatives inherent in the current state of dry electrodes, to include: 1) multiple rigid prongs that require sustained pressure to penetrate hair and maintain solid scalp contact, creating higher levels of discomfort when compared to standard wet sensors; 2) cumbersome or chin-strap-type applications for maintaining electrode contact, decreasing the likelihood of end user acceptance; 3) rigid active electrodes to compensate for high input impedances that limit flexibility and placement of sensors; 4) inability to safely imbed sensors under protective headgear, restricting use in some fields where EEG metrics are most desired; and 5) expensive sensor manufacturing that drives costs high for use across subjects. When objectively evaluating existing dry sensors vs. current wet technologies, intended application should be taken into consideration. For short term recordings (i.e., less than 8 hours), evidence suggests that available wet sensors are the more effective option, while for acquisitions over 8 hours in length dry sensors may prove beneficial. Another viable option for future wearable sensors is to extend the 8 hour recording time of existing wet sensors.

Under a DARPA Phase 3 contract, we were able to consider both possibilities as possible end solutions for long acquisitions. Solution 1 entailed the design of a dry hydrogel sensor that was soft, flexible, and embeddable, eliminating all of the main drawbacks associated with existing dry sensor technologies. The design process allowed the dry sensor to be interchangeable with our current wet (i.e., foam and synapse cream) sensors, while maintaining the same usability across head sizes and hair types. Some of the results from a 9 subject study are included, along with additional single subject studies on the most recent advances and modifications of the dry sensor.

Solution 2 involved improving the ease-of-use of the current wet systems to ultimately enable the end user to self-adjust the system, quickly and easily changing out the sensors as needed without any additional support. This development would permit long term recordings with wet sensors. Some early prototype solutions are highlighted in the Discussion section.

2 Methods and Materials

2.1 Methods

As part of the Phase 3 DARPA contract, the Advanced Brain Monitoring, Inc. (ABM) dry sensor prototype was integrated with a proprietary EEG system and tested as part of a live performance requirement. A total of 9 subjects (1 female; ages: 22- 39) participated in the study, with each of the 3 dry electrode teams providing 3 subjects. The subjects rotated through a 3 day testing sequence across all 3 teams. The procedure complied with the appropriate Institutional Review Board (IRB), and each subject provided written consent prior to cap application. For each day of testing, 3 subjects were set up with the dry sensor interface (average set-up time of less than 5 minutes), with one subject each day repeating the session as part of a wet/dry comparison. Each subject was run through a battery of tests that took approximately 90 minutes from set-up to break down. Session recordings included the following tasks: a Baseline session of Eyes Open (EO), Eyes Closed (EC), Eye Blinks, and EMG; SSVEP at 5, 10, and 15 Hz; a Baseline SSVEP EO for 2 minutes; a Rapid Serial Visual Presentation (RSVP) Video task; an RSVP Image task (with Novelty Image) and Evoked Response Potential (ERP) Task; and an Audio ERP task. As a follow-up to the live performance requirement, 2 additional subjects (2 male; ages 22 and 25) were run through the full test battery in house, using further iterations of the semi-dry interface. Changes are discussed in the Materials section, and the results and outputs were comparable to those of the earlier 9 subjects. For purposes of this paper, the results will focus on data from the RSVP Image Task (with Novelty Image) n =11. Future papers will discuss the results of other tasks performed.

The experimental task for RSVP presented 25 sets of 50 images. Each set of images comprised 49 terrain images and 1 novelty Mickey Mouse image. Use of the novelty image elicited pronounced ERPs even in shorter test sessions. Images remained on screen for 0.2 seconds each, for a total duration of 10 seconds per set. The user was provided a 2 second pause between each set of 50 images. After every 5 sets, a longer 10 second break was provided to the subject. Users were instructed to use pauses for resting and/or blinking eyes to help minimize artifacts during testing.

To obtain ERP measures, the EEG was visually inspected for artifacts and data containing muscle artifacts or eye blinks were excluded from analysis.

To accommodate differences across dry electrode teams, the comparison between wet and dry sensor types required the following set-up. All teams recorded dry sensor data from F3, F4, P3, and P4, in addition to their remaining sensor sites (which differed between teams), while simultaneously recording wet data from F5, F1, F6, F2, P5, P1, P6, and P2. For the ABM team, this entailed removing existing sensor sites at F1, F2, P1 and P2 to accommodate the wet sensor set-up. The wet sensor data was then used to create derived F3, F4, P3, and P4 channels. Differential channels F3P3 and F4P4 were then calculated and compared between the wet and dry. For the purpose of this paper, P3 and P4 were used to show the PSD correlations from the baseline EO and EC tasks and to look at Target and Non-Target ERPs from the RSVP with Novelty.

2.2 Materials

Data for all of the ABM team's dry studies was collected using Advanced Brain Monitoring, Inc.'s commercially available B-Alert X24 Wireless EEG Headset System sampling at 256Hz for all channels. The sensor montage used for data acquisition was developed in part under previous DARPA contracts, optimized for single trial ERP analysis. Sensor sites collected were F3, F1, Fz, F2, F4, C3, C1, Cz, C2, C4, CPz, P3, P1, Pz, P2, P4, POz, O1, Oz, and O2 according to the extended International 10-20 placement. All sites were referenced to Linked Mastoids in the wireless mode. The standard wet sensors were replaced with the semi-dry sensors for data collection. The semi-dry sensor consists of a hydrogel (i.e., water absorbing polymer) with dissolved hygroscopic ingredients/components to maintain hydration, and dissolved salts to conduct electricity ionically. Maintaining hydration ensures the salts stay dissolved and that the sensors retain lower skin-to-sensor impedances for longer periods of time. The hydrogel was polymerized around a cylinder of silverized spacer fabric attached to conductive (i.e., silverized) hook Velcro. This spacer fabric served 2 important roles: 1) a structural support for the hydrogel, and 2) a transition to the fabric strip. The strip that connected to the B-Alert X24 Wireless EEG Headset was a stretchable fabric that utilized silverized thread with an insulative, polymer coating applied via chemical vapor deposition (CVD) to each of the fabric strip layers to carry the signals from the semi-dry sensor to the hardware. The stretchable fabric strip was used across all 9 subjects during data acquisition. Two additional subjects were added to the data set after the required test run, using the standard commercial strip interfaced with the semi-dry sensor, bringing the subject total to the n=11 used for group summaries found in the Results section.

For wet recording comparisons, the g.TecUSBamp 16 channel, 24-bit digitizer was used, sampled at 256Hz. Set-up of the 8 wet EEG sensor sites and the ground and reference on the earlobes required abrasions at each site and alcohol prep. All impedances were required to be below 5 kΩ prior to recording data.

3 Results

3.1 Dry vs. Wet Comparison

The EEG signal shown in Fig. 1 is derived wet F4P4 compared to the actual dry derived F4P4 montage. The signals demonstrate the similarities between the wet and dry sensors, despite the steps involved to obtain each derived differential recording.

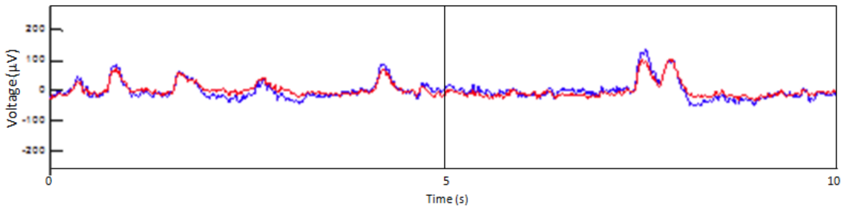

Fig. 1. Ten seconds of ABM (blue) and G.Tec. (red) EEG trace for F4P4

Subsequent comparisons between wet and dry sensors are shown using P3 and P4 to reduce the amount of data manipulation required. Figure 2 shows the PSD 1-40Hz between the dry and derived wet signal at P3 for 30 second recordings of EO, and EC recorded during the baseline session.

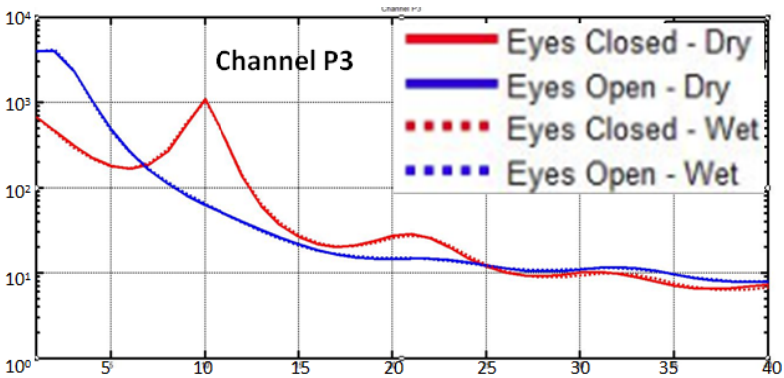

Fig. 2. 2 PSD 1-40Hz wet-dry

ERPs are shown in Figure 3 from subject 0104, recorded during the wet/dry comparison. Shown are the averaged ERPs for Target and Non Target images recorded from the dry P3 and P4 and derived wet P3 and P4 sites.

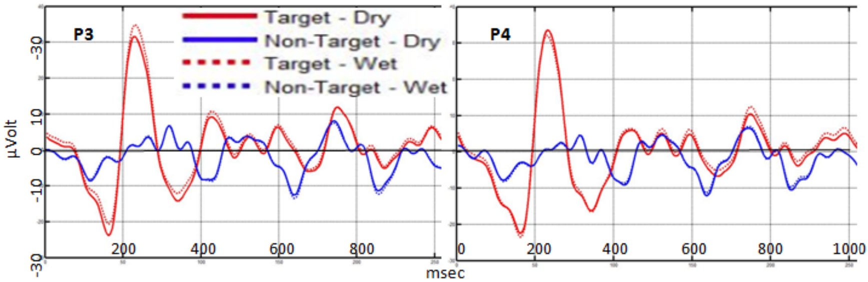

Fig. 3. Mean ERP from wet-dry comparison at P3 and P4

3.2 Grand Mean Results for Dry RSVP (n = 11)

The RSVP paradigm with Novelty was collected on 11 total subjects. All ERP graphs are shown in µVolts on the x-axis and milliseconds on the y-axis. The grand means are shown in Figure 4. We were able to obtain ERPs for all 20 sensor sites and data from 4 of the dry sensor sites are presented herein for the Mean average across subjects and the individual subject ERPs. These sites represent some of the typical ERP components across all sites. Figure 5 shows ERPs for an individual subject (ID 0102) on day one of testing, representing their first time through the test battery.

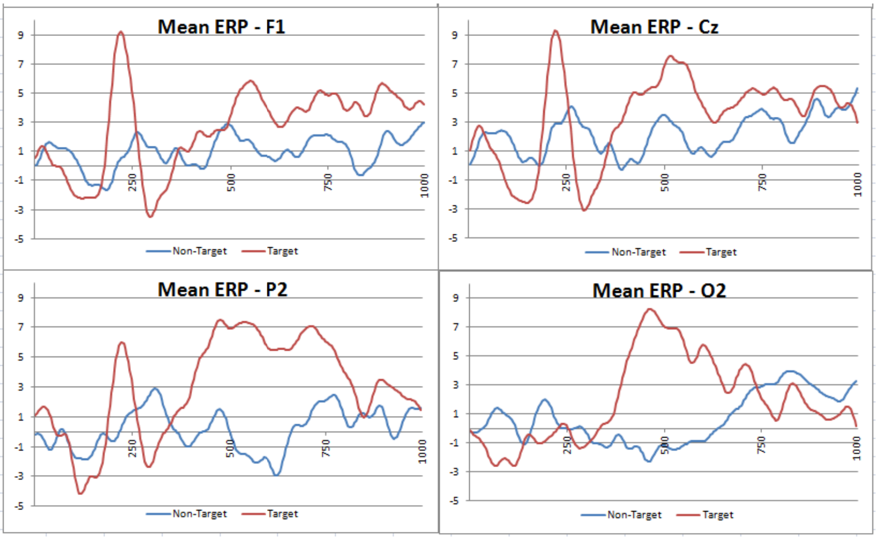

Fig. 4. Mean ERP 11 subjects Target vs. Non-Target sites F1, Cz, P2, and O2

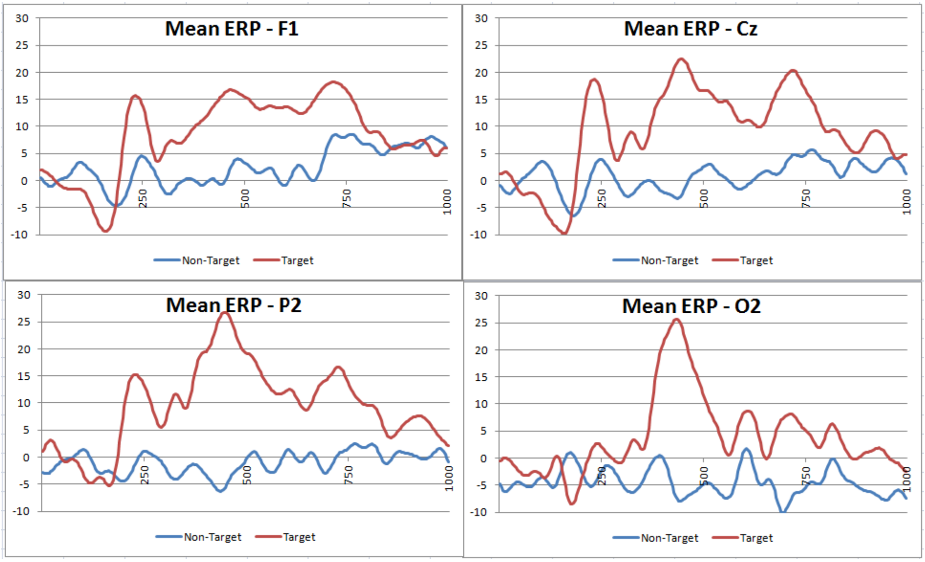

Fig. 5. Mean ERP ID0102 Target vs. Non-Target F1, Cz, P2, and O2

Figure 6 shows ERPs for individual subject (ID 0303) on day three of testing, representing their third time through the test battery. While fatigue is evident in the subject and the P300 is reduced in P2 and O2, the early P100/N200 amplitude differences still appear in F1, Cz, and P2. Figure 7 shows ERPs for another individual subject (ID 0402) on their first run through the test battery, collected after the live test run using the commercial strip interfaced with the semi-dry sensors.

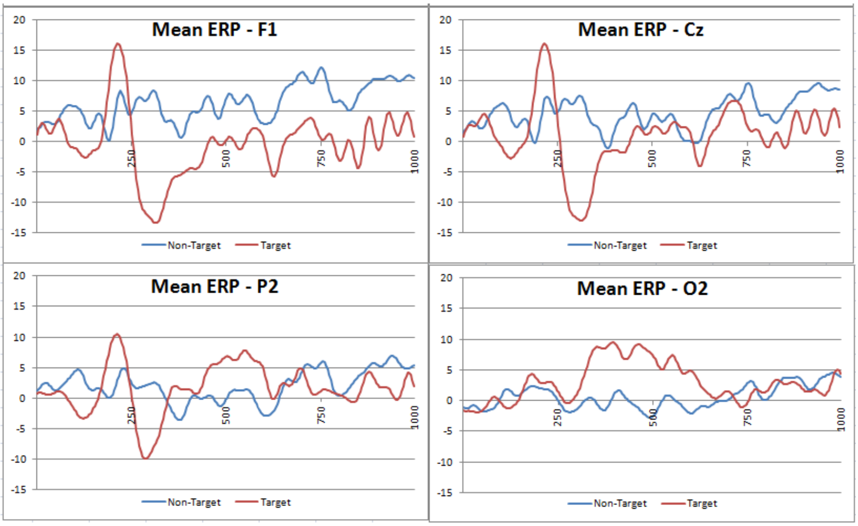

Fig. 6. Mean ERP ID 0304 Target vs. Non-Target for sites F1, Cz, P2, and O2

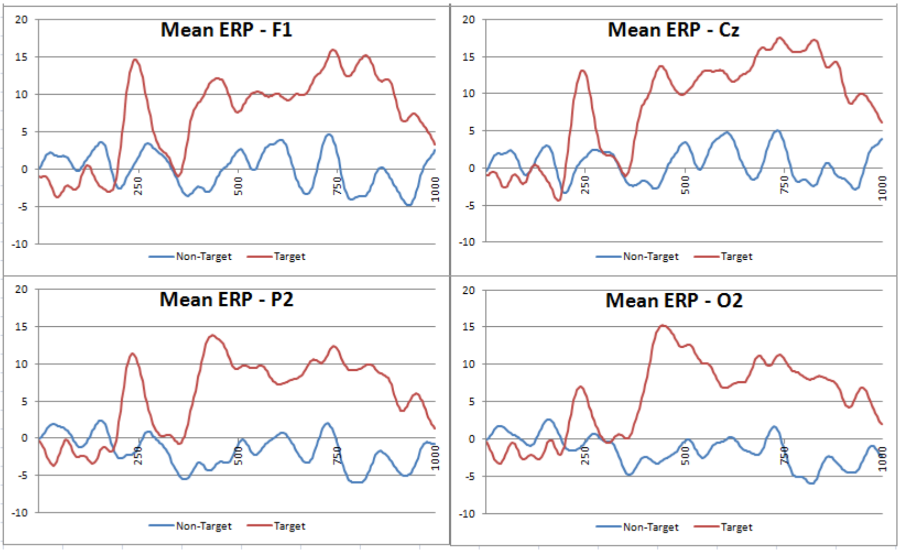

Fig. 7. Mean ERP ID 0402 Target vs. Non-Target for sites F1, Cz, P2, and O2

4 Discussion

The novel semi-dry hydrogel sensor tested in this paper proved to be a comparable alternative to the conventional (now superseded) 10/20 wet paste system. Due to the design of the all-soft semi-dry sensor, which has no rigid components, it was also able to address the main shortcomings of existing dry electrodes, providing a true real world wearable solution.

The data becomes even more compelling when considered alongside the manner in which it was collected; rather than a controlled lab wired acquisition on one or two sensor sites, EEG data was collected wirelessly as part of a live performance requirement with a 20 sensor site montage. Each day of testing included 4 sessions, each 2 hours in length, to allow for a full test battery that included set up, multiple paradigms, and break down. Once per day, one of the set-ups included a wet/dry comparison requiring real time modifications to the system to accommodate the wet sensor placements that overlapped with dry sensors. To provide common subjects across teams, all 9 subjects rotated to a new team each day with 1 subject from each team completing both a dry and a wet/dry session each day. The rotation resulted in some subjects completing 6 full sessions by the end of day 3, while the remaining subjects would each complete 3 sessions by the end of day 3.

Despite the repetition of the test battery for 6 of the 9 subjects, the Mean ERPS for Target vs. Non-Target still resulted in prominent P100, N200, and P300 features for each individual. Fatigue and repetition had the largest impact on the P300 components, but the amplitude difference between the P100 and the N200 peaks remained significant throughout testing as seen in Figure 6, iteration three for the subject.

After the completion of the live performance requirement, ABM conducted additional test runs on further iterations of the dry strip interface. While the stretchable conductive fabric used for the first 9 subjects shows great promise, the current manufacturing expenses may prove cost-prohibitive. Testing following the live performance was conducted on alternative applications of the current commercial strip that will allow rapid sensor change outs from a prepackaged form factor. The new packaging works with both the semi-dry hydrogel sensor and the currently used easy-to-apply foam and synapse cream sensor. The ERPs collected from subsequent tests with the new strip show the same ERP components from the live performance test on the group of 9. Ongoing additional testing continues to support equivalence between the two dry strip interfaces.

ABM plans to continue refining the dry sensor, ultimately arriving upon a commercially available dry sensor option that the end user can switch between depending on the goals and applications of the intended study.

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References

1. Berger, H.: uber das Elektroenkephalogramm des Menschen. Eur. Arch. Psychiatry Clin. Neurosci. 87, 527–570
2. Guger, C., et al.: Comparison of dry and gel based electrodes for P300 brain-computer interfaces. Front. Neurosci., doi:10.3389/fnins.2012.00060
3. Wang, L., et al.: PDMS-Based Low Cost Flexible Dry Electrode for Long-Term EEG Measurement. IEEE Sensors Journal 12(9) (September 2012)
4. Slater, J., et al.: Quality Assessment of Electroencephalography Obtained From a “Dry Electrode” system. Journal of Neuroscience Methods 208, 134–137 (2012)
5. Forvi, E., et al.: Preliminary Technological Assessment of Microneedles-Base Dry Electrodes for Biopotential Monitoring In Clinical Examinations. Sensors and Actuators A 180, 177–186 (2012)
6. Dias, N.S., et al.: Wireless Instrumentation System Based on Dry Electrodes for Acquiring EEG Signals. Medical Engineering & Physics 34, 972–981 (2012)
7. Ghoshdastider, U., et al.: Development of a Wearable and Wireless, Modular, Multichannel, EEG-System Utilising Dry-Electrodes for Long Time Monitoring. Biomed Tech. (2012), doi:10.1515/bmt-2012-4056
8. Berka, C., et al.: Real-Time Analysis of EEG Indexes of Alertness, Cognition, and Memory Acquired With a Wireless EEG Headset. International Journal of Human-Computer Interaction 17(2), 151–170 (2004)
9. Stevens, R., et al.: Modeling the Neurodynamic Complexity of Submarine Navigation Teams. Computational and Mathematical Organization Theory (2012)

10. Berka, C., et al.: Accelerating Training Using Interactive Neuro-Educational Technologies: Applications to Archery, Golf, and Rifle Marksmanship. International Journal of Sports and Society 1(4), 87–104
11. Chung, J.W., et al.: Treatment Outcomes of Mandibular Advancement Device for Obstructive Sleep Apnea Syndrome. Chest 140, 1511–1516
12. Westbrook, P., et al.: Description and Validation of the Apnea Risk Evaluation System: a Novel Method to Diagnose Sleep Apnea-Hypopnea in the Home. Chest 128, 2166–2175
13. Behneman, A., et al.: Neurotchnology to Accelerate Learning. NEST (2012) (in Press)