Validation of a Dry Electrode System for EEG

Justin R. Estepp[1], James C. Christensen[1], Jason W. Monnin[1], Iris M. Davis[2], Glenn F. Wilson[3]
[1]Air Force Research Labs, 711th Human Performance Wing [2]Ball Aerospace [3]Physiometrix, Inc.

Electroencephalography (EEG) has been used for over 80 years to monitor brain activity. The basic technology of using electrodes placed on the scalp with conductive gel or paste ("wet electrodes") has not fundamentally changed in that time. An electrode system that does not require conductive gel and skin preparation represents a major advancement in this technology and could significantly increase the utility of such a system for many human factors applications. QUASAR, Inc. (San Diego, CA) has developed a prototype dry electrode system for EEG that may well deliver on the promises of dry electrode technology; before any such system could gain widespread acceptance, it is essential to directly compare their system with conventional wet electrodes. An independent validation of dry vs. wet electrodes was conducted; in general, the results confirm that the data collected by the new system is comparable to conventional wet technology.

INTRODUCTION

Previous research has shown that psychophysiological measurement based on EEG data can be used to detect and categorize a variety of mental states, with applications including workload evaluation, adaptive automation, and brain-computer interfaces (Berka, et al., 2004; Birbaumer & Cohen, 2007; Freeman, Mikulka, Prinzel & Scerbo, 1999; Gevins, et al., 1998; Shelley & Backs, 2006; Wilson & Russell, 2003a; 2003b). A major drawback to the use of EEG data in human factors research is the preparation and expertise required when working with current EEG technology: to collect good quality data, electrode sites on the scalp must be cleaned and then have conductive gel applied to form an electrical connection with the metal of the electrode. This connection can have limits, due to scalp irritation over prolonged or repeated data collection. An electrode system that does not require this site preparation or conductive gel thus offers many advantages: experimental preparation time is reduced substantially, variability due to gel drying or inexpertly applied electrodes is reduced, and the length of studies may be extended, including repeated data collection. In addition to the advantages for the experimenter, such a system also represents a major advancement in comfort and convenience for participants, which expands the environments in which it may be used.

"Dry" electrodes that offer these advantages have been studied for many years (Searle and Kirkup, 2000), with notable success in the collection of electrocardiographic (ECG) and electromyographic (EMG) signals. However, both ECG and EMG signals are much stronger than EEG, and the production of a system that is both sensitive enough to detect EEG as well as robust to noise and reliable over time has proven difficult. Fonseca et al (2007) may have developed such an electrode, but their report is primarily focused on materials and fabrication with minimal human testing and no examination of muscle artifact. Fonseca's electrode at least offers advantages over Taheri et al. (1994) in terms of durability. QUASAR, Inc. has been developing dry electrode technology for some time, and has produced several prototypes of a system based on a high impedance hybrid capacitive/resistive electrode (Matthews et al, 2005; 2007)

To test if this system produces EEG data comparable to conventional wet electrode technology, two pieces of information are required: data collected simultaneously from dry and wet electrodes sited as close together as possible, and data from wet electrodes placed at the same sites to provide a baseline for comparison. In an effort to conduct a thorough test of the system, a variety of conditions designed to produce variation in both cortical signals and electrophysiological artifact were run, including resting eyes open and closed, a verbal n-back task (Kirchner, 1958) previously demonstrated to produce workload-related variation in EEG (Krause et al, 2000), and a variety of artifact-producing movements including jaw, head, shoulder and eye movements. Given how new the QUASAR system is, durability over extended testing cannot be assessed, though the system has been used for ~40 hours with no noticeable differences.

METHODS

Six participants completed the study, including four males and two females, between the ages of 20 and 45 years. Three participants were laboratory personnel; the rest were paid volunteers. Participants completed comprehensive written informed consent document prior to participating. All participants had hair, varying in length from ~1cm to greater than 15 cm. The dry electrode system tested was a prototype system produced by QUASAR, designed for Command and Control (C2) applications (Figure 1).

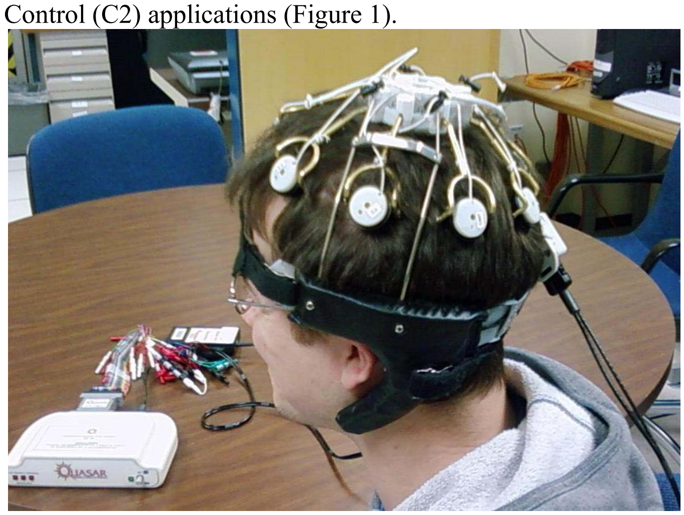

Figure 1. The prototype QUASAR dry electrode system for electroencephalographic recording.

10.1518/107118109X12524443346077

The system consists of a headset incorporating eight of QUASAR's hybrid electrodes, located at F3, Fz, F4, C3, Cz, C4, and Pz, with the reference located at P3 in addition to a grounding strap across the forehead. This headset is connected to a QUASAR amplifier and a BioRadio 110 wireless physiological telemetry system (Cleveland Medical Devices Inc.; Cleveland, OH), with BioRadio Capture, a software package for the BioRadio, running on a PC for real-time data collection and visualization.

The wet electrodes used were single lead Ag/AgCl electrodes attached to the scalp with collodion, as close to the dry electrodes as was practicable without direct contact, resulting in a mean center-to-center separation of 20mm. The forehead ground was used for wet as well as dry electrodes. The dry system used the dry electrode at P3 for reference while the wet electrodes used the P3 offset wet electrode for a reference. The dry electrode output went through QUASAR's amplifier, and then all signals were digitized through the same wireless transmitter. Because of a limitation in the BioRadio 110 on the number of available data channels, Fz, C4 and Pz were selected for data collection (with a dry/wet electrode pair at each site, for a total of 6 data channels). By selecting sites distributed across different lobes of the brain, it was hoped a representative data sample would be collected (Figure 2).

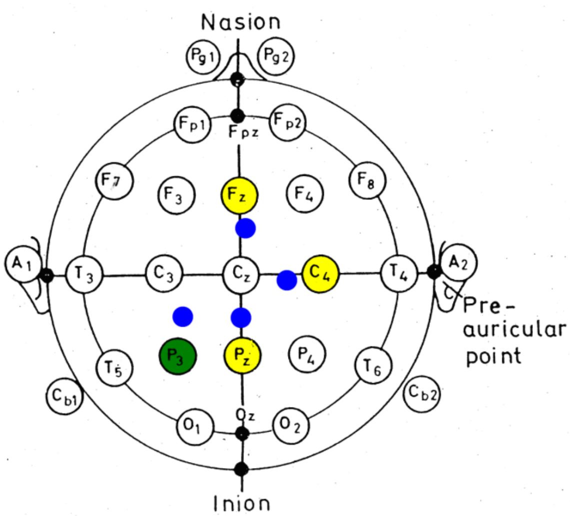

Figure 2. The scalp sites tested, according to the International 10-20 System for Electrode Placement. The filled yellow sites are the locations of the dry electrodes, the green site is the dry electrode reference, and blue dots indicate the location of the wet electrodes for one representative participant. Differences in head size and shape led to variations wet electrode placement , never exceeding 10mm in any direction from the intended location.

Participants were instructed on the computer-based n-back task and allowed to complete one five-minute block to practice. Electrodes were then applied, with wet electrode sites prepped with alcohol cleaning and a mild abrasive (Nuprep gel, Weaver and co., Aurora, CO), followed by the use of collodion to affix the leads to the scalp and the injection of conductive gel (Electrogel, ECI, Eaton, OH). Impedance was measured at less than 5 kOhms for each wet electrode prior to beginning the study. For three participants, the dry electrode headset was then placed in a pre-measured position to ensure placement on standard 10-20 locations. No preparation or additional treatment of any kind was applied to the dry electrode sites. The other three participants served as control participants, with additional wet electrodes placed in the dry electrode locations to provide a baseline comparison between pairs of wet electrodes for evaluating the dry/wet pairs. Participants then completed, in randomized order, two blocks each of four conditions: eyes closed, eyes open, the n-back task, and an artifact condition designed to produce electrophysiological artifacts wherein the participants were asked to sequentially move their jaw, eyes, head, and shoulders for approximately 15 seconds each, with 10 seconds in between. This last condition was intended to determine if the dry electrodes were equally susceptible to artifacts as compared to the wet electrodes. Each block of the study lasted approximately 5 minutes, with 60 seconds to rest and reset software in between blocks. The n-back task was run with only a 2-back condition on a desktop PC, with performance data collected and analyzed to ensure that participants were successfully performing the task. Total time to complete the run averaged slightly less than one hour; during debriefing the only discomfort reported was associated with the dry electrode headband and not the electrodes themselves.

RESULTS

Data were collected with a sampling frequency of 200 Hz and band pass filtered between .5 and 52.4 Hz prior to analysis. To quantify the similarity between the signals collected from two different electrodes, Pearson correlations of the electrode-pair time-domain signals (similar to those shown in Figure 3 and Figure 4) were calculated. Many other measures could be used, but the correlation will provide a representative estimate of the similarity. All correlation values reported are *r* values.

Figure 3 is a representative time-domain sample drawn from the eyes-closed condition for one participant, using the data collected from two wet electrodes. This provides the baseline for comparison with the dry electrodes. Figure 4 presents similar traces, but comparing dry and wet electrodes. Looking at the data as a function of frequency, there are no consistent differences in power as a function of frequency between the dry and wet electrodes, except perhaps a slight decrease in 60 Hz noise in the dry electrodes, similar to that observed by Fonseca et al (2007). Figures 5 and 6 present power spectral densities for the eyes open and eyes closed conditions, comparing dry and wet electrodes. Similar plots for the wet vs. wet control are essentially completely overlapping and not presented.

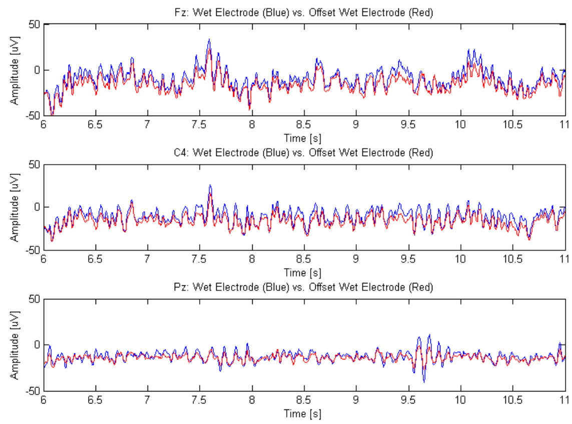

Figure 3. Representative five-second samples of EEG traces taken from pairs of wet electrodes placed in the same configuration as the dry/wet combinations at three scalp sites. Slight differences are observed, providing a baseline for the dry/wet comparison.

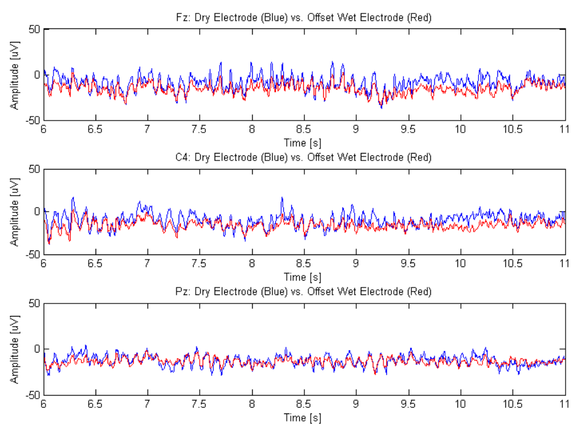

Figure 4. Representative five-second samples of EEG traces taken from dry (blue lines) and wet (red lines) electrodes simultaneously at the three scalp sites.

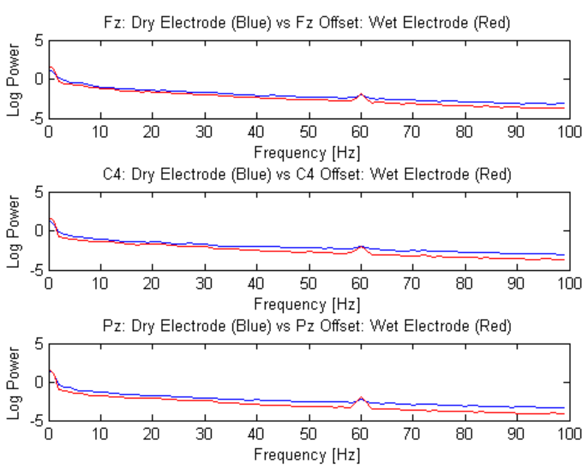

Figure 5. Power spectral densities plotting log power as a function of frequency for the dry and offset wet electrodes, averaged across participants in the eyes-open baseline condition. The dry electrodes appear to attenuate 60 Hz line noise somewhat as compared to the wet electrodes.

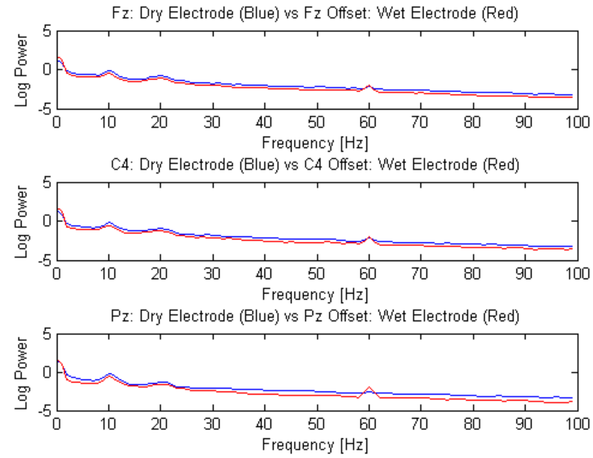

Figure 6. Power spectral densities averaged across participants for the eyes-closed condition, comparing the dry and wet electrodes. The expected increase in alpha band power (~10Hz in this case) as compared to the eyes-open condition is observed.

The jaw clench in the artifact run produced the highest power of any of the motions tested and was examined in some detail. The response of the dry electrodes is not noticeably different from the wet electrodes, excepting perhaps a slight difference in power at low frequencies: Figures 7 and 8 present time domain plots of an example jaw clench, while 9 and 10 present the power spectral densities. The high power of the jaw clench did not lead to large differences in the power spectral densities.

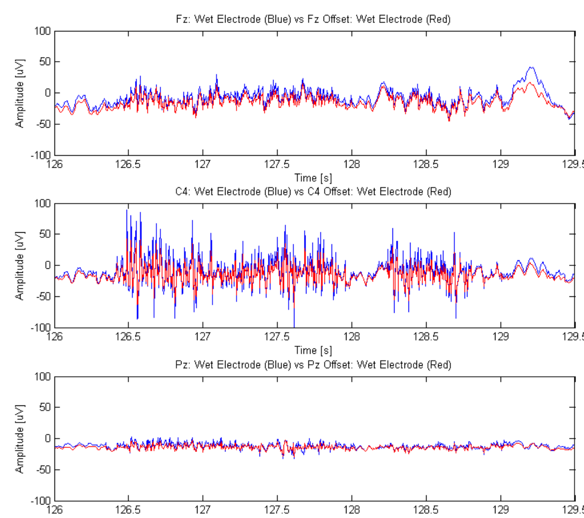

Figure 7. Time domain data for an example jaw clench for the wet vs. wet electrode control condition.

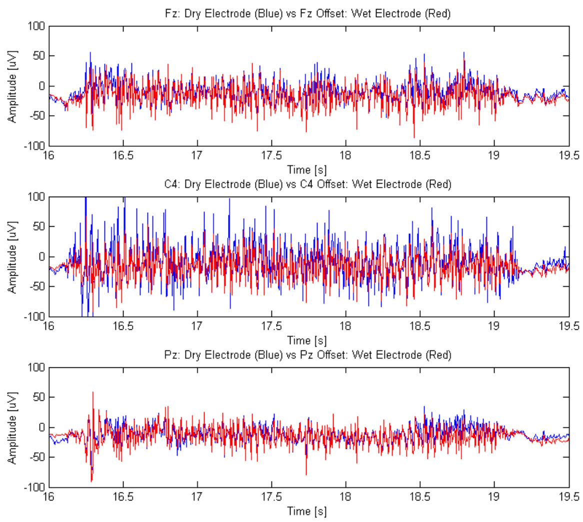

Figure 8. Time domain data for a similar jaw clench for the dry vs. wet electrode condition.

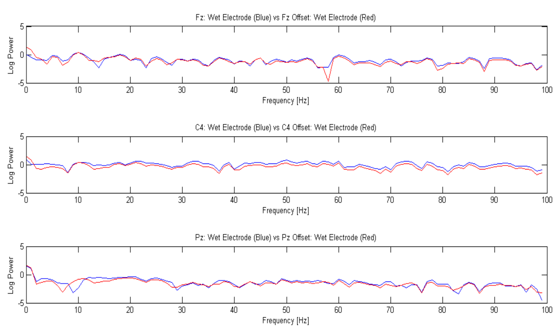

Figure 9. Power spectral density for the data from figure 7, averaged across participants.

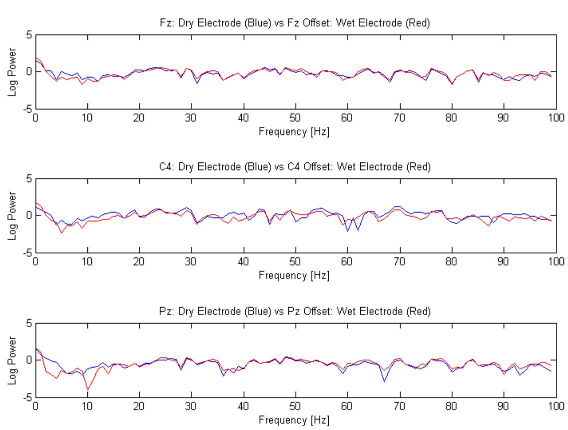

Figure 10. Power spectral density for the data from Figure 8, averaged across participants.

Across task conditions and participants, the overall correlation between the data collected from two wet electrodes varied between sites, from a high of .96 at the frontal site to a low of .80 at the parietal site. The overall correlations between dry and wet electrodes were significantly lower than in the baseline wet to wet comparison but still high, ranging from .85 at the frontal site down to .39 at the parietal site. There were no significant differences in the correlations obtained from different task conditions. Tables 1 and 2 present the complete results of these correlations, calculated across participants.

WET v WET

	Fz	C4	Pz
Eyes Closed	0.97	0.95	0.80
Eyes Open	0.97	0.96	0.83
n-Back	0.97	0.96	0.79
Artifact	0.97	0.96	0.82

Table 1. Correlations between pairs of wet electrodes matching the configuration of the dry/wet pairs, listed by scalp site and task condition. Note the decreasing trend from front to back on the head (Fz higher than C4 higher than Pz).

WET v DRY

	Fz	C4	Pz
Eyes Closed	0.82	0.71	0.45
Eyes Open	0.84	0.61	0.32
n-Back	0.88	0.67	0.37
Artifact	0.83	0.72	0.42

Table 2. Correlations between pairs of dry and wet electrodes, listed by scalp site and task condition. Note again the decreasing trend from front to back, similar to the results obtained with all wet electrodes.

DISCUSSION

These results demonstrate that the QUASAR system is capable of collecting EEG data that is comparable to that collected via conventional wet electrodes. The correlations observed between wet and dry are significantly lower than those between wet and wet electrodes, particularly at posterior sites. However, the fact that good correlations between dry and wet electrodes were achieved in frontal sites across all conditions and with varying hair types is a significant improvement in EEG technology.

The different task conditions demonstrate that the similarity of the dry system to wet electrodes is robust across a variety of tasks, including relatively severe muscular artifact induced by jaw clenching and head and shoulder motion; while still in progress and not reported here, we have also collected limited pilot data suggesting that the robustness of the dry system extends to recording EEG in an ambulatory environment. This would be a vast improvement over traditional wet-electrode EEG, which may be susceptible to large artifact associated with gross movement (change in posture, walking, running, etc.).

There were differences in the correlations achieved as a function of electrode site. The three sites were chosen from the seven available in order to sample locations on the front, middle, and back of the head. An unexpected result was that correlations for both wet to wet and wet to dry electrodes went down from the front to the back of the head. Testing is still ongoing investigating the source of this decreasing similarity; it seems unlikely that there are larger local differences at the back of the head than the front. Variation in hair thickness or mechanical pressure could have affected the dry electrodes, but does not explain the similar results with wet electrodes, and thus is insufficient to explain this. One possibility that is being examined is that the parietal reference is simply too close to the parietal electrode site, resulting in signal as well as noise being subtracted the closer the site is to the reference. If this is the case, a change in reference location should improve or eliminate this problem.

The QUASAR system stands in contrast to other commercial systems touted as collecting EEG signals without preparation or gel that likely collect the much-easier signals originating from muscles in proximity to the scalp (Heingartner, 2009). Further development will almost certainly improve the accuracy and reliability of this dry electrode system. However, as tested, this system is capable of recording EEG signals with fidelity in some cases approaching that achieved with conventional wet electrodes.

Conflict of Interest Statement:

The authors of this paper state that they have no financial interest in QUASAR, Inc., and derive no personal profit or gain from the success or failure of this dry electrode system.

REFERENCES

Berka, C., Levendowski, D. J., Cvetinovic, M. M., Petrovic, M. M., Davis, G., Lumicao, M. N., Zivkovic, V. T., Popovic, M. V., & Olmstead, R. (2004). Real-Time Analysis of EEG Indexes of Alertness, Cognition, and Memory Acquired With a Wireless EEG Headset. *International Journal of Human-Computer Interaction*, 17, 151-170.

Birbaumer, N., & Cohen, L. G. (2007). Brain-computer interfaces: communication and restoration of movement in paralysis. *Journal of Physiology* , 579, 621-636.

Fonseca, C., Silva-Cunha, J.P., Martins, R.E., Ferreira, V.M., Marques de Sá, J.P., Barbosa, M.A., Martins da Silva, A. (2007). A novel dry active electrode for EEG recording. IEEE Transactions on Biomedical Engineering, 54(1), 162-165.

Freeman, F., G., Mikulka, P. J., Prinzel, L. J. & Scerbo, M. W. (1999). Evaluation of an adaptive automation system using three EEG indices with a visual tracking task. *Biological Psychology*, 50, 61-76.

Gevins, A., Smith, M. E., Leong, H., McEvoy, L. K., Whitfield, S., Du, R., & Rush, G. (1998). Monitoring working memory load during computer-based tasks with EEG pattern recognition methods. *Human Factors*, 40(1), 79-91.

Heingartner, D. (2009). Loser: Mental Block. *IEEE Spectrum,* February 2009. Downloaded on 2/2009 from http://www.spectrum.ieee.org/jan09/7086.

Kirchner, W. K. (1958). Age differences in short-term retention of rapidly changing information. *Journal of Experimental Psychology*, 55(4), 352-358.

Krause, C.M., Sillanmäki, L., Koivisto, M., Saarela, C., Häggqvist, A., Laine, M., Hämäläinen, H. (2000). The effects of memory load on event-related EEG desynchronization and synchronization. *Clinical Neurophysiology*, 111: 2071-2078.

Matthews, R., McDonald, N. J., Fridman, I., Hervieux, P., and Nielsen, T. (2005).The invisible electrode – zero prep time, ultra low capacitive sensing," presented at the 11th International Conference on Human Computer Interaction (HCII), Las Vegas, NV, July 22-27, 2005.

Matthews, R., McDonald, N. J., Anumula, H., Woodward, J., Turner, P.J., Steindorf, M. A., Chang, K., and Pendleton, J. M. (2007) "Novel hybrid bioelectrodes for ambulatory zero-prep EEG measurements using multi-channel wireless EEG system," in *Foundations of Augmented Cognition: Third International Conference, FAC 2007*, Proceedings of the 12th International Conference on Human Computer Interaction (HCII), Beijing, July 22-27, 2007. pp 137-146.

Russell, C. A., Wilson, G. F., Rizki, M., Webb, T. & Gustafson, S. (2005). Comparing classifiers for real time estimation of cognitive workload. *Proceedings of the 11th International Conference on Human-Computer Interaction,* Vol 11, Foundations of Augmented Cognition.

Russell, C. A., and Wilson, G. F. (2005) Feature saliency analysis for operator state estimation. *Proceedings of the 11th International Conference on Human-Computer Interaction*, Vol 11, Foundations of Augmented Cognition.

Searle, A. & Kirkup, L. (2000). A direct comparison of wet, dry and insulating bioelectric recording electrodes. *Physiological Measurement*, 21(0), 183-271.

Shelley, J. & Backs, R. W. (2006). Categorizing EEG waveform length in simulated driving and working memory dual-tasks using feed-forward neural networks. *Foundations of Augmented Cognition.* Strategic Analysis, Inc,. (pp. 155-161).

Taheri, A., Knight, R., & Smith, R. (1994) . A dry electrode for EEG recording. *Electroencephalography and Clinical Neurophysiology*, 90, 376–83.

Wilson, G. F. & Fisher, F. (1991). The use of cardiac and eye blink measures to determine flight segment in F4 crews. *Aviation, Space and Environmental Medicine*, 62, 959-961.

Wilson, G. F. and Russell, C. A. (2003a). Operator functional state classification using psychophysiological features in an air traffic control task, *Human Factors*, 45, 635-643.

Wilson, G. F. & Russell, C. A. (2003b). Real-time assessment of mental workload using psychophysiological measures and artificial neural networks, *Human Factors*, 45, 635-643.

Wilson, G. F. & Russell, C. A. (2007). Performance enhancement in a UAV task using psychophysiological determined adaptive aiding. *Human Factors*, 49, 1005-1019.