Comparative Results of Simultaneous Evoked Response Potential Measurements Using Dry Contact Electrodes and Conventional Wet Electrodes

Abstract

Practical sensing of biopotentials such as the electroencephalogram (EEG) in operational settings has been severely limited by the need for skin preparation and conductive electrolytes at the skin-sensor interface. Another seldom-noted problem has been the need for a low impedance connection from the body to ground for cancellation of common-mode noise voltages. In this article we describe EEG results acquired using EEG hardware based upon dry contact electrode technology, and which uses a proprietary common-mode follower (CMF) which allows a high impedance dry electrode to be used for the ground.

The performance levels for dry contact electrodes are generally found to be comparable to conventional wet electrodes [1]. This article presents results auditory evoked potential measurements using Wearable Sensing's DSI-24 system simultaneously with conventional (wet) EEG electrodes. The correlations between wet and dry electrodes (averaged over 3 subjects) were 93.6% and 95.7% for F3-P3 and F4-P4, respectively.

Introduction

An analysis of the relative performance of two electrode technologies is limited by the fact that the electrodes cannot be co-located. This leaves the experimenter with two alternatives: sequential testing of the two electrode technologies using separate trials, for which the EEG is assumed to be stationary, or using nearby electrodes to approximate signals for use in the comparison. The assumption of stationarity can only be regarded as being partially met during EEG measurements, and is readily violated by subject fatigue. This can be problematic in Evoked Response Potential (ERP) measurements, where the subject is required to concentrate over extended periods. Simultaneous recordings using both electrode types is preferable as both electrodes will measure the time evolution of the same brain sources, albeit with a bias due to their different locations. The reader is referred to Saab *et al.* and references cited therein for a discussion of methods used elsewhere for comparisons of the performance of dry and wet electrodes, in which it is noted that the performance levels for dry contact electrodes are generally found to be comparable to conventional wet electrodes [1].

Previous measurements on the sensor technology utilized in the DSI-24 EEG headset have observed 90% correlation between wet and dry electrodes in spontaneous EEG [2]. In 2009, Air Force researchers evaluated an EEG headset using this technology on 19 subjects and reported "results confirm that the data collected by the new system is comparable to conventional wet technology" [3]. More recently, researchers and epileptologists at the Texas Comprehensive Epilepsy Program of the University of Texas Health Science Center at Houston (UTHSC), conducted a clinical evaluation of a similar headset using this technology, and determined that data quality is suitable for diagnosing status epilepticus and seizure activity [4].

This article presents results for simultaneous measurements of auditory ERPs using dry and wet electrodes. In these measurements, the bias due to different electrode locations is minimized by taking the averages of several nearby electrodes to approximate the signal at a central location.

Methods

Experimental Design

A total of 9 subjects were selected for testing of QUASAR's EEG hardware, according to an IRB-approved protocol. Signed informed consent was obtained from each subject. From these 9 subjects, 3 were selected at random for the wet/dry electrode comparison measurements described in this article.

The auditory ERP task used a tone generation routine (200 tones on PC speakers, average interval 2 seconds) to stimulate ERP signals. A trigger signal was output for each tone on a single line on the parallel port of the PC. The trigger signal was connected to the trigger inputs of EEG hardware: Wearable Sensing's DSI-24 EEG headset and a gTec USBamp (gTec Medical Engineering GmbH, Austria).

EEG Hardware

Subjects wore Wearable Sensing's DSI-24 EEG headset (Figure 1), which includes integrated dry electrode biosensors positioned at approximate standard International 10/20 electrode locations. The headset has been designed such that it can be put on by a minimally trained person without assistance, and record EEG through-hair without the need for skin preparation of any kind.

Electrophysiological measurements using dry contact biosensors are enabled by a proprietary common mode follower (CMF) technology. The CMF is a separate biosensor located at Pz that is used as a reference for bioelectric measurements so that the common-mode signal appearing on the body is dynamically removed from the measurements. It operates by measuring the potential of the body relative to the ground of the amplifier system. The ultra-high input impedance of the CMF (~10^{12} Ω) ensures that the output of the CMF tracks the body-ground potential with a high degree of accuracy.

Wet electrode measurements were acquired using Ag/AgCl EEG electrode cups filled with Grass EC2 conductive EEG paste (Astro-Med, West Warwick, RI) and attached to sites on the subject's scalp. The electrode sites were cleaned with alcohol to remove fats and then abraded with NuPrep (Weaver & Co., Aurora, CO). Wet electrode signals were acquired using a gTec USBamp system (Figure 2). The gTec system is a 24-bit, 16-channel EEG system with a single trigger input.

Experimental

The headset was donned by the subject without preparation of the dry electrode sites. Once the DSI-24 headset was donned and the biosensors were correctly located at the 10/20 electrode locations, each biosensor was manipulated through the subject's hair until adequate contact was established. Adequate contact was defined as a contact impedance less than 1 MΩ, measured using a 110Hz impedance signal. The CMF was also manipulated through the hair until adequate contact (< 1 MΩ) was established. For the CMF, contact impedance was measured using a 130Hz impedance signal.

After adequate contact was established for the DSI-24 sensors, the F1, F5, F2, F6, P1, P2, P5, P6 electrode sites were prepared for wet electrodes. These electrode sites were selected because they straddled the 10/20 locations F3, F4, P3 and P4. The ground and reference electrodes for the gTec system were placed on prepared sites on the subject's right earlobe and pinna, respectively.

During ERP measurements the subject was asked to focus upon an X appearing on the PC. EEG data were acquired at 300 samples per second (sps) for the DSI-24 system, and 600 sps for the gTec system.

Figure 1 – Wearable Sensing's DSI-24 EEG headset.

Figure 2 – gTec USBamp EEG amplifier.

Data Analysis

The F3, P3 and F4, P4 electrode pairs on the headset were combined in software to form the anterior-posterior bipolar signals F3-P3 and F4-P4. The equivalent signals for the wet electrodes were approximated by combining the wet electrode signals thus:

F3-P3 ≈ (F1+F5)/2 – (P1+P5)/2
F4-P4 ≈ (F2+F6)/2 – (P2+P6)/2

i.e. the bipolar signals F3-P3 & F4-P4 are estimated using the average of the electrodes straddling the corresponding 10/20 electrode locations.

The F3-P3 & F4-P4 signals were digitally filtered using Infinite Impulse Response (IIR) notch filters to remove impedance carrier signals (110Hz & 130Hz), mains interference (60Hz) and then bandpass filtered to produce EEG data in a 1-40Hz bandwidth (-3dB). Identical filtering was applied to both DSI-24 and gTec data. ERP epochs were obtained by taking an interval [-0.5s, +0.5s] around each trigger. The final ERP signals were taken as the average of all epochs in which the filtered signal magnitude did not exceed 50 µV. The wet electrode ERP data was then decimated by a factor of two by averaging consecutive data points to generate an ERP signal with a sample rate of 300 sps. The sample correlation coefficient was then calculated between the average dry electrode ERP and average wet electrode ERP signals.

Results

The results for all three subjects are presented in Figure 3, which plot the average ERP signals in the interval from 500ms preceding the trigger to 500ms following a trigger. Correlations between wet and dry electrodes (averaged across 3 subjects) for the intervals shown are **93.6% and 95.7% for F3-P3 and F4-P4**, respectively. In addition, average signal to noise ratios (SNRs) for ERP amplitude over pre-trigger noise RMS voltage across 3 subjects and vectors were 11.8 ± 5.5 and 12.6 ± 2.2 for dry and wet recordings respectively, indicating equivalent SNR.

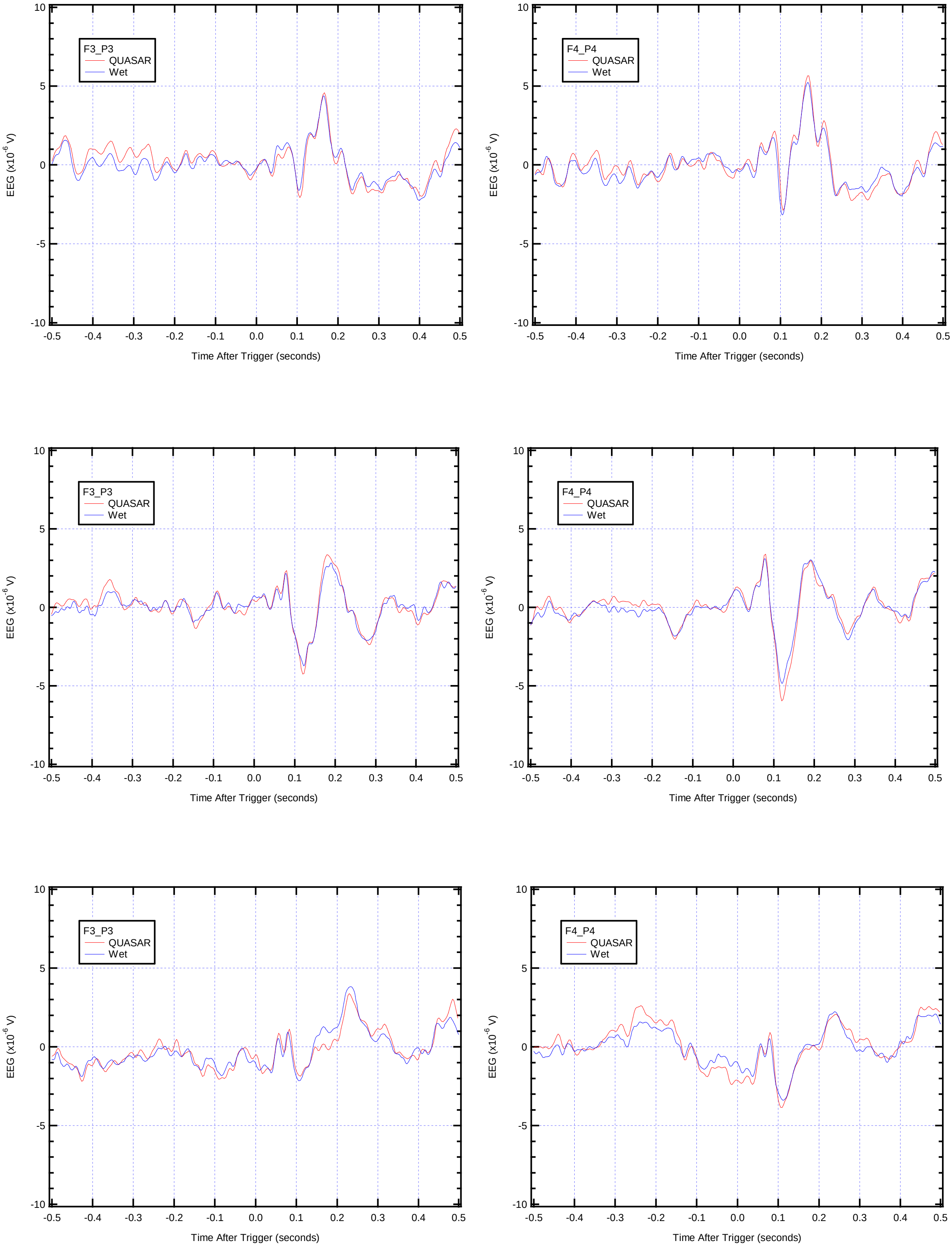

Figure 3 – Average auditory ERP signals of 200 trials for dry electrodes (red) and wet electrodes (blue), for 3 subjects at 2 different vectors (F3-P3, left, and F4-P4, right).

Discussion

Simultaneous measurements of ERP signals using dry electrode and wet electrodes excellent conservation of signal morphology between signals obtained from wet and dry electrodes; both in the pre-trigger “noise” segment, and in the N100-P200 ERP component. This is evident both in a visual inspection of the traces presented in Figure 3,, and also by the fact that the correlation values exceed 90% for both anterior-posterior ERP signals and that the SNRs for both electrode technologies are equivalent.

References

[1] Saab, J., Battes, B. & Grosse-Wentrup, M. (2011) Simultaneous EEG Recordings with Dry and Wet Electrodes in Motor-Imagery. In *Proceedings of the 5th Int. Brain-Computer Interface Conference*, Verlag der Technischen Universität Graz, Graz, Austria, pp. 312-315

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[3] Estepp JR, Christensen JC, Monnin JW, Davis IM, Wilson GF (2009) Validation of a Dry Electrode System for EEG. In: Proceedings of the Human Factors and Ergonomics Society, pp 1171-1175. San Antonio, Texas.

[4] Slater, J.D., Kalamangalam, G.P., Hope, O. (2012). Quality Assessment of Electroencephalography Obtained From a "Dry Electrode" System. *Journal of Neuroscience Methods.* Vol. 208, pp 134-137.

Appendix

This Appendix presents details of the signal processing used in our ERP analysis, where sufficient detail has been included for the reader to replicate the results presented in the body of this article.

The following sections have been organized according to the sequence of steps involved in the analysis, namely:

- Data Format
  Step 1: Loading data
- Channel Map
  Step 2: Assignment of EEG electrodes to input data
- Data Scaling
  Step 3: Obtain input-referred signals for each EEG channel
- Bipolar Signals
  Step 4: Calculate bipolar channels F3-P3 and F4-P4
- Signal Filtering, Filter Design & Filter Coefficients
  Step 5: Filter EEG signals to remove mains interference @ 60Hz, to remove EEG headset impedance carrier signals @ 110Hz and 130Hz, and bandpass the data between 1-40Hz (-3dB)
- Triggers
  Step 6: Trigger Detection
- Timing Offset
  Step 7: Remove timing delays in EEG headset data
- ERP Epoch
  Step 8: Select region around each trigger
- Thresholding
  Step 9: Apply threshold to remove ERPs that are corrupted by artifacts
- ERP Signal
  Step 10: Generate averaged ERP signal
- Downsampling
  Step 11: Downsample the wet electrode data to a sample rate of 300 sps
- Correlation
  Step 11: Calculate correlations between averaged ERP signals for dry and wet electrodes

Data Format

Data are supplied in comma separated value (CSV) format, which is the native output format of the EEG headset. For the convenience of the reader, the gTec data have been converted to CSV format using a script written in MatLab (MathWorks Inc., Natick, MA, USA).

EEG headset data include a header that comprises the first line and contains channel labels. In these measurements, the electrode locations were not downloaded to the headset, and so the reader is referred to "Channel Map" for assigning electrode locations to each column of data.

Each EEG headset data file has 28 columns of data. EEG data are reported in columns 5-28. Time data are reported in column 2. The values in column 2 are clock ticks since the headset was last synchronized with the PC, where the system clock uses 1800 ticks per second. Therefore, at a sample rate of 300 sps the time column advances by 6 ticks per reading. Trigger data are reported in column 4. The remaining 2 columns are used for diagnostic purposes and can be ignored.

gTec data possess no header information. As for the headset data, the reader is referred to “Channel Map” for assigning electrode locations to each column of data. Each gTec data file has 17 columns of data. EEG data are reported in columns 1-16. Trigger data are reported in column 17. No timing information is included. gTec data were acquired using a sample rate of 600 sps.

Channel Map

The electrode locations for EEG headset data and gTec data are presented in Table 1.

Table 1 – Channel Map of electrode locations for DSI-24 EEG Headset and gTec EEG measurements.

EEG Headset Data Column #	EEG Headset Channel	EEG Headset Electrode Location
2	TimeOffset	
4	Trigger	
5	ch_1	P3
6	ch_2	C3
7	ch_3	F3
8	ch_4	Fz
9	ch_5	F4
10	ch_6	C4
11	ch_7	P4
12	ch_8	Cz
13	ch_9	CM
14	ch_10	M1
15	ch_11	Fp1
16	ch_12	Fp2
17	ch_13	T3
18	ch_14	T5
19	ch_15	O1
20	ch_16	O2
21	ch_17	N/C
22	ch_18	N/C
23	ch_19	F7
24	ch_20	F8
25	ch_21	N/C
26	ch_22	M2
27	ch_23	T6
28	ch_24	T4

gTec Data Column #	gTec Electrode Location
17	Trigger
1	F1
2	F2
3	F5
4	F6
5	P1
6	P2
7	P5
8	P6
9	N/C
10	N/C
11	N/C
12	N/C
13	N/C
14	N/C
15	N/C
16	N/C

Note that for the EEG headset data electrodes are only positioned at the International 10-20 electrode locations. This is a total of 21 electrode sites, even though the hardware supports 24 channels of data. Three channels are reported as Not Connected (N/C). The ch_9 data (CM) is the common-mode signal appearing on the body and which is removed by the reference electrode. This signal was acquired with reduced gain because of the large common-mode signals observed during subject motion.

Data Scaling

The EEG headset data were output as bits. In contrast, the gTec data were output as microvolts. The analysis performed converted the data to *volts at the input of the electrode*. Table 2 presents the scaling factors applied to each set of data.

Table 2 – Scale factors to convert reported values to volts at input of electrode.

Scaling Factor	EEG Headset	gTec USBamp
Volts per bit	1.9272×10^{-5}	N/A
Sensor Gain	64.3	1×10^{6}

Referred-to-input voltages, V_{RTI}, are obtained from the reported voltages, V_{meas}, using the following equation:

$$V_{RTI} = V_{meas} \times \frac{Volts\ per\ bit}{Sensor\ Gain}$$

In order to obtain a referred-to-input voltage for the CMF channel for EEG headset data, V_{RTI} must be reduced by a further factor of 247.

Bipolar Signals

The anterior-posterior bipolar channels F3-P3 and F4-P4 were calculated for the EEG headset and gTec data. For the gTec data, the F3-P3 and F4-P4 bipolar signals were approximated by:

F3-P3 ≈ (F1+F5)/2 – (P1+P5)/2
F4-P4 ≈ (F2+F6)/2 – (P2+P6)/2

i.e. the bipolar signals F3-P3 & F4-P4 were estimated using the average of the electrodes straddling the corresponding 10/20 electrode locations.

Signal Filtering

Signal filtering included notch filters to remove mains interference @ 60Hz, to remove EEG headset impedance carrier signals at @ 110Hz and 130Hz, and further filtering to provide EEG data in a 1-40Hz bandwidth. Identical filtering was applied to both EEG headset and gTec data, even though the gTec impedance signal was turned off, and furthermore has no signals at 110Hz or 130Hz.

Signal filtering used the following steps for each EEG channel:

- Apply 60Hz mains notch filter
- Apply 110Hz notch filter
- Apply 130Hz notch filter
- Apply 40Hz low pass filter
- Remove the filter ringing at the beginning of the data by setting the 1st 0.5 seconds of the filtered EEG channel to be equal to the filtered output, $V_{out,0.5s}$, @ 0.5 seconds

- Subtract $V_{out,0.5s}$ from the filtered EEG channel
- Apply 1Hz high pass filter

The steps prior to application of the high pass filter were used to minimize the duration of filter ringing after application of the high pass filter. For filters with low corner frequencies this is evident as a baseline drift, and occurs over a timescale that is several times the time constant for the filter. In the case of the gTec data, a step function was often seen at the beginning of the file, presumably due to digital filtering of the signal within the gTec device prior to output, that would possess filter ringing for longer than 10 seconds.

Filter Design

Digital filters were designed using the Igor Filter Design Laboratory (IFDL) package (WaveMetrics Inc., Portland, OR, USA). The IFDL package was used because the automatic design of filters in some filter design packages did not meet our requirements. Specifically, Bessel filters were preferred because of their phase response in the passband, whereas the MatLab filter design for Bessel filters (besself) only generates low-pass Bessel filter designs. Alternatively, filter designs obtained using Scientific Python appear to have greater roll-off at specified corner frequencies as the number of poles increase.

More significantly, both filter packages design filters of the direct form, which can become unstable as the number of poles in the filter increases. The filters designed using the IFDL package were cascaded bi-quad filters. The discussion below explains the implementation of a direct and cascade filters.

An Infinite impulse response (IIR) filter's transfer function in zero-pole form is:

$$H(z) = K \prod_{k=1}^{N} \frac{z - z_k}{z - p_k}$$

In the direct form, the filter transfer function can be written as an Nth order polynomial in $\frac{1}{z}$:

$$H(z) = \frac{Y(z)}{X(z)} = \frac{a_0 + a_1 z^{-1} + \cdots + a_N z^{-N}}{b_0 + b_1 z^{-1} + \cdots + b_N z^{-N}}$$

where *Y(z)* is the Z-transform of the output signal and *X(z)* is the Z-transform of the input signal. Cross multiplying gives

$$Y(z)[b_0 + b_1 z^{-1} + \cdots + b_N z^{-N}] = X(z)[a_0 + a_1 z^{-1} + \cdots + a_N z^{-N}]$$

The equivalent time domain "difference" equation is computed by substituting x[i-n] for $X(z)\, z^{-n}$ (an inverse Z-transformation), and similarly for y and *Y(z)*, and then solving for the digital time-domain output signal y[i]:

$$y[i] = \frac{1}{b_0}\{a_0 x[i] + a_1 x[i-1] + \cdots + a_N x[i-N] - b_1 y[i-1] - b_2 y[i-2] - \cdots - b_N y[i-N]\}$$

The instability in the direct form is due computing differences in terms with greatly varying magnitudes as N increases.

An alternative favored in video and audio processing is to use a cascaded approach, in which the filter is separated into individual bi-quad sections, each with filter order 2 or less (i.e. N=2). Therefore an 8-pole filter would be represented as a cascade of 4 sections of 2nd order filters. The output of the first filter is used as an input to the next filter, and so forth until the output of the final filter returns the filtered signal.

Filter Coefficients

In this section we provide the details of the IIR digital filters used in our analysis. Bessel filters were used because they possess approximately linear phase delay in the passband (i.e. constant group delay). This represents a compromise with respect to other IIR filter designs (e.g. Butterworth, Chebyshev) that possess faster roll-off, but which have significantly less linear phase delay.

The filter coefficients for all filters are presented in Table 3 to Table 7.

Table 3 – IIR filter coefficients for 60Hz notch filter (Q=10).

Sample Rate	a_0	a_1	a_2	b_0	b_1	b_2
300 sps	0.938676059246	-0.580133736134	0.938676059246	1	-0.579201757908	0.878284096718
600 sps	0.968856871128	-1.56764340401	0.968856871128	1	-1.56720197201	0.938155114651

Table 4 – IIR filter coefficients for 110Hz notch filter (Q=10).

Sample Rate	a_0	a_1	a_2	b_0	b_1	b_2
300 sps	0.888783097267	1.18942403793	0.888783097267	1	1.18410456181	0.782885670662
600 sps	0.943583190441	-0.767579734325	0.943583130836	1	-0.766620576382	0.888125538826

Table 5 – IIR filter coefficients for 130Hz notch filter (Q=10).

Sample Rate	a_0	a_1	a_2	b_0	b_1	b_2
300 sps	0.868706882	1.58720648289	0.868706822395	1	1.57835865021	0.746261537075
600 sps	0.933850049973	-0.388316661119	0.933850049973	1	-0.387519180775	0.868497550488

Table 6 – IIR filter coefficients for 40Hz (-3dB) 7-pole low-pass Bessel filter.

Sample Rate	a_0	a_1	a_2	b_0	b_1	b_2
300 sps	0.00595634570345	0.0119126914069	0.00595634570345	1	-0.126650169492	0.386872947216
	1	2	1	1	-0.23674082756	0.149158582091
	1	2	1	1	-0.275578945875	0.0491836071014
	1	1	0	1	-0.142903491855	0

Sample Rate	a_0	a_1	a_2	b_0	b_1	b_2
600 sps	0.000200743437745	0.000401486875489	0.000200743437745	1	-1.02782976627	0.509319484234
	1	2	1	1	-0.979064583778	0.324760556221
	1	2	1	1	-0.95348328352	0.246259436011
	1	1	0	1	-0.472728550434	0

Table 7 – IIR filter coefficients for 1Hz (-3dB) 3-pole high-pass Bessel filter.

Sample Rate	a_0	a_1	a_2	b_0	b_1	b_2
300 sps	0.981815159321	-1.96363031864	0.981815159321	1	-1.9790738821	0.979281008244
	1	-1	0	1	-0.984289288521	0

Sample Rate	a_0	a_1	a_2	b_0	b_1	b_2
300 sps	0.990857720375	-1.98171544075	0.990857720375	1	-1.98953437805	0.989586412907
	1	-1	0	1	-0.992113888264	0

Triggers

For the EEG headset, each entry in the Trigger column is the decimal representation of the headset's 8-bit trigger input (=0 in the absence of a trigger). For these measurements the trigger signal was input to bit 0. Therefore the presence of a trigger is indicated by a 1.

For the gTec system, each entry in the Trigger column is either 0 (NO TRIGGER) or 250000 (TRIGGER).

Triggers within the first 10 seconds of the data record are ignored.

Timing Offset

EEG headset data are acquired at a sample rate of 1200 sps. The firmware then applies a digital finite impulse response (FIR) filter to anti-alias the data prior to decimation to an output rate of 300 sps. This is the sample rate for data passed to the PC. The FIR filter introduces a delay that is one half of its length, which corresponds to a timing shift, relative to a trigger signal, equivalent to 16 data points at a sample rate of 300 sps.

No such correction was applied to the gTec data.

ERP Epoch

The ERP epoch was defined to be the interval [-0.5s, 0.5s] around each trigger.

Thresholding

A threshold was applied to the filtered EEG signal in each ERP epoch. If the signal magnitude in any epoch exceeded 50 µV then that epoch was not used to generate the averaged ERP signal.

ERP Signal

The filtered signals for all ERP epochs that were not rejected after thresholding were averaged.

Downsampling

In order to obtain a correlation value between dry and wet electrode data, the data from the two systems must be at the same data rate. In our analysis, we simply averaged consecutive gTec data points using:

$$gTec_{300sps}[n] = \frac{1}{2}\left(gTec_{600sps}[2n] + gTec_{600sps}[2n+1]\right)$$

where n is the point index for the 300 sps data.

Correlation

The correlation is calculated as the sample correlation coefficient, r_{xy}, to estimate the Pearson product-moment correlation coefficient, given by:

$$r_{xy} = \frac{\sum_{i=1}^{N}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\left\{\sum_{i=1}^{N}(x_i - \bar{x})^2\right\}\left\{\sum_{i=1}^{N}(y_i - \bar{y})^2\right\}}}$$

where the x_i are EEG headset data, the y_i are gTec data, and N is the number of points in each data set.