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**Accounting for Timing Drift and Variability in
Contemporary Electroencephology (EEG) Systems**

by W. David Hairston

ARL-TR-5945

March 2012

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ARL-TR-5945

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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188		
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1. REPORT DATE (DD-MM-YYYY) March 2012		2. REPORT TYPE Final		3. DATES COVERED (From - To) July–August 2011	
4. TITLE AND SUBTITLE Accounting for Timing Drift and Variability in Contemporary Electroencephalography (EEG) Systems			5a. CONTRACT NUMBER		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) W. David Hairston			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory ATTN: RDRL-HRS-C Aberdeen Proving Ground, MD 21005-5425			8. PERFORMING ORGANIZATION REPORT NUMBER ARL-TR-5945		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSOR/MONITOR'S ACRONYM(S)		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT Electroencephalography (EEG) data acquisition technology is rapidly advancing. Because it is now more feasible to use in operational environments, its use in Army-relevant applications has also increased. However, integration of EEG with other systems requires the synchronization of multiple data modalities and identification of potential sources of error. Here, we assess the degree of stimulus timing drift and encoding jitter associated with several contemporary EEG systems. The measured amount of drift and jitter is then applied to several waveforms, including simulated, real evoked potentials, and data from a “phantom” head model for the sake of assessing the functional impact of each variable. Results show a wide range of drift across systems and particularly high timing variance in one; simulations show the potential for a dramatic distortion of signals if unaccounted for within those systems with more than 0.01% drift relative to an external clock. Additional simulations show a severe impact of encoding variance. We discuss a correction algorithm, with evidence that it not only alleviates distortion caused by drift but can also improve the results yielded from signal-averaging analyses in the case of high-variance systems.					
15. SUBJECT TERMS EEG, evaluation, variability, validation					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON W. David. Hairston
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			UU

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1. Introduction

1.1 Background

Over the last decades, the field of neuroscience has grown tremendously, as has our understanding of how the brain works in action. This growth has prompted scientists to apply this knowledge to the needs of the U.S. Army and find ways to leverage neuroscientific techniques to enhance the lives of our Soldiers. For example, the area of brain-activity-sensing technologies, such as electroencephalography (EEG), has traditionally been viewed as being useful only as a laboratory technique with limited operational application. However, recent advances in the headset, electrode, and related data-acquisition technologies prove very promising for the transition to more practical Army applications regarding devices used within the U.S. Department of Defense (DOD) research and development (R&D) community, as well as increased plausibility for field-deployable units.

However, because transitioning EEG into operational settings remains a burgeoning area with relatively little research history, it is important to empirically evaluate the current state of the art in equipment and assess areas of potential problems to see where improvements need to be made to guide further development. In many ways, the very metrics for evaluating EEG systems themselves (in a way that is meaningful for scientists) are not well defined or standardized across the R&D community. As a result, the Translational Neuroscience Branch is endeavoring to facilitate the translational pathways necessary for moving EEG into U.S. Army operational usage. A substantial component of this translation is evaluating the efficacy of current EEG hardware solutions.

EEG is commonly used to derive a correlation between some type of brain activity and a task or specific cognitive event. In doing this, neuroscientists examine EEG data within specific temporal windows, relative to the onset or occurrence of an event or series of events. Typically data is recorded continuously while several different events or types of events occur, spread out over time (anywhere from minutes to hours); data is then binned into discrete sections of time (epochs) based on when the events occurred, yielding an event-related response.

One caveat to this type of approach is that the timing of the recording systems must be accurate and precise; many neural responses of interest are very fast and transient (on the order of milliseconds) and may not be properly captured and represented if the recording system is inconsistent. That is, if the stated times that events occurred do not consistently represent the actual time, then the brain response to be examined will not appear accurately, especially when examining an average of several events and responses. Thus, it is critical to be aware of the degree of timing accuracy/consistency of any system to be used in this manner.

1.2 Jitter and Drift

This report outlines two specific areas of potential concern related to event timing within contemporary EEG systems: encoding jitter and temporal drift. Encoding jitter refers to variability between the time that an event is stated or reported to have occurred and when it actually occurs. Within an EEG data stream, there are at least two primary sources where jitter can occur. The first stems from inconsistency or unreliability of the device that creates the stimulus or event to which the participant is responding. That is, there is some difference in time between when the device is said to have begun creating the stimulus (such as a function call within a computer script) and when the physical stimulus arrives (such as a sound wave coming out of a speaker). These types of inconsistencies, often described as stimulus-related jitter, usually originate from devices that are not built for the timing specifications of the task at hand or perhaps from asynchronous operating frequencies between devices (such as a CPU call to draw a picture on a monitor that refreshes at only 60 Hz). The second, recording-related jitter, occurs when there is variability or asynchrony in the system that is recording the occurrence of events and tying this to the EEG data stream. In most conventional EEG systems, this would be related to the accuracy or sample rate of the digital-to-analog converter (DAC) device or software routines (such as buffering) used in the recording system to integrate the signals. In this report, we are primarily targeting this source of jitter as it relates to specific recording systems.

Temporal drift occurs when there is a slow, cumulative difference in time coefficients of two or more systems. It is primarily related to having two independent clocks that may not be exactly 100% synchronous with one another. When clocks are out of synchrony, the times that events occur relative to one clock will “drift away” from reports of the other. In EEG, a PC is often used to provide stimuli to a subject (e.g., play sounds, present video) which logs events based upon that PC’s internal clock. Meanwhile, the EEG system itself typically has its own clock (based on the DAC) that is of a different (lower) sampling rate and in many cases is run off of a second PC. “Time” relative to the EEG is then converted from its own sample rate to seconds or milliseconds, based on an assumed sample rate (e.g., 512 Hz); however, if the actual rate is slightly different (e.g., 512.001 Hz), then an asynchrony is introduced.

This drift is commonly alleviated by using synchronizing data triggers. Virtually all modern EEG systems have some means of receiving information from external systems; that information is integrated with the EEG data stream online (see section 2 for several examples). This may be done through communication over a parallel, serial, or network port (if using multiple PCs), Transmission Control Protocol (TCP), or direct function calls to pass data between stimulus and recording programs within the PC collecting data. By doing so, data representing the timing of external events is added to the EEG data, sampled within the same time and rate, and thus is natively in-synchrony with it.

However, situations commonly arise where data originally recorded online are not sufficient for current needs, and information must be gathered from a second log file. For example, an

experimenter may realize during data analysis that he or she would like to examine evoked potentials related to the exact time at which the participants pressed a button in response to a scene flashed on a screen. Although the response times were not embedded with the EEG during the data collection, the experimenter has a detailed log of the events and subjects' responses, which were created by the program running the experiment. The experimenter could easily extract the necessary data from this second log file; however, because the response times were logged using a different clock system, they are not necessarily on the same time scale and may be out of synchrony with the original EEG. If the data were then binned based on those externally encoded times, it could introduce a progressive error when comparing across many trials.

1.3 Objectives

There are three primary objectives for this report. First, we aim to assess the typical encoding jitter and timing drift observed within four different commercially available EEG systems—three contemporary wireless systems (manufactured by Advanced Brain Monitoring, Emotiv Systems, and Quasar Inc.) and one traditional wire-based system (Biosemi). Second, we highlight the effects on both real, empirically derived, and simulated EEG data, and the consequences if these factors are not appropriately accounted for and drift occurs in the data. Finally, we discuss methods that can correct timing inconsistencies and show the efficacy of those methods for not only correcting drift, but also potentially improving the timing fidelity beyond that of the initial recording.

2. Methods

2.1 Hardware Configuration

The overall configuration consisted of two PCs plus the EEG systems being tested. The primary EEG data acquisition (“DAQ”) PC was a Dell Precision 690 running Windows XP SP3, connected to the following EEG systems (with their respective acquisition software versions): Advanced Brain Monitoring X10 (Be-Alert 2.45*), Biosemi Active2 (ActiView 6.05), Emotiv Epoc (TestBench 1.5.0.3), and Quasar Helmet-Mounted System (HMS) (QStreamer 1.5.1046). All systems were connected to the acquisition PC through a USB hub. The stimulus-trigger-generating (“STIM”) PC was a Dell Optiplex GX620 PC, also running Windows XP SP3. For Advanced Brain Monitoring (ABM) and Biosemi systems, this STIM PC was connected directly to the EEG systems using a 25-pin parallel port into an integration box that was part of each EEG DAC system. For Quasar HMS, this parallel port signal was converted to a single transistor-

* In response to feedback during testing, Advanced Brain Monitoring provided a firmware update that improved the timing drift observed in their DAC unit. We include here results from both the original and updated versions (referred to as “ABM-A” and “ABM-B”) for additional comparison.

transistor logic (TTL) binary pulse, as that is the only available method of trigger input for that system. The Emotiv Epop system used a serial connection (RS-232, 57,600 bps) between the two PCs, relying on the DAQ PC and acquisition software for online integration. E-Prime 2.0 (Psychology Software Tools, Inc.) was used to send stimulus trigger pulses (during testing) and record pulse receipt times (during calibration verification). This general configuration (two separate PCs) was chosen because it is a common scenario for behavioral research labs, and it is the most likely case for temporal drift and jitter artifacts to occur. During all tests, only one EEG system was active at a time.

2.2 Calibration

The primary factors of interest in this report are the encoding jitter and temporal drift observed in several commercially available EEG data acquisition systems. Encoding jitter in this case is defined as variability (in \pm millisecond standard deviations) in the reported time of arrival of a signal, relative to a known-quantity time at which it actually occurred. Temporal drift refers to an increasing difference over time between the reported time of arrival and the known time at which it occurred, and is reported as a fractional rate.

In order to quantify both of these factors, they must be compared against a known-quantity, consistent, standard signal. To establish the reliability of our standard signal, we first used a calibrated function generator (Tektronix AFG320) to send a 1-Hz square wave to the DAQ PC using a BNC-to-DB25 adapter to connect to the PC's parallel port, simulating a TTL-level signal. The time of arrival of the leading edge of each waveform was recorded using E-Prime; these times were confirmed to line up consistently within ± 0.3 ms with no notable drift over a 10-min recording window. This confirms that the parallel-port/E-Prime combination can reliably (within <1 -ms precision) report pulse times, and that the DAQ PC clock does not drift relative to a calibrated source. As a second step, parallel-port triggers were sent (10-ms pulse, every 100 ms) using E-Prime from the STIM PC and recorded using E-Prime on the DAQ PC. These were confirmed to be within ± 0.3 ms variance in time of arrival (jitter) and showed no notable increase in difference (drift) over the 10-min record, affirming that the output of the STIM PC using E-Prime is functionally equivalent to that of the calibrated function generator and the system clocks of the two PCs did not drift relative to one another within a typical EEG recording timescale.

2.3 Timing Test Paradigm

To test the consistency and drift in recorded times for each EEG system, a digital value code was sent from the STIM PC every 1250 ms and recorded using the native acquisition software for each EEG system. This timeframe was chosen because it is not evenly divisible by the native sample rate of any of the systems (ABM: 256 Hz; Biosemi: 512 Hz; Emotiv: 128 Hz; Quasar: 240 Hz) and thus would avoid any aliasing effects and maximize the average number of cases where the trigger arrival time fell between sample periods across systems. This is also within the range of a typical time between stimuli or trials for many behavioral tasks. Five hundred triggers

were sent, covering a total of 10.42 min, as this ensured a large sample size as well as fairly lengthy time that a participant might perform a typical event-related task. No EEG data were recorded during these times, as only the trigger timing was of interest.

2.4 Waveform Simulation With Phantom

In order to highlight the functional effects of timing jitter and drift on the estimation of an EEG signal, it was necessary to use a known-quantity signal for comparison that could be detected using a standard EEG system. This was done using an EEG “phantom” head prototype device created by Creare, Inc., in conjunction with Army Small Business Innovative Research Award no. A10-066. The device is a mannequin-style head shape made of multiple conductive layers approximately analogous to the human brain, skull, and skin in both physical shape and electrical conductance, containing several open-ended electrode leads encapsulated within the “brain” material. Using the calibrated function generator, we created a single 10-Hz sine wave that was passed through an electrode located approximately within the frontal cortex region of the device. The device was triggered at regular intervals in order to simulate a “response” that could be measured at the scalp analogous to a typical event-related potential (ERP).

2.5 Simulated Data

To highlight the functional effects of system variance and drift on a continuous signal, the error was simulated by application to a square waveform. The initial (basis function) waveform rose from 0 to 1 at time 100 ms, returning to 0 after a 100-ms period. This was repeated 200 times with 4-s inter-stimulus-interval (ISI) for a total length of 13.33 min, to simulate a typical experimental trial length interval and typical total time of a single test. Effects of drift, jitter, and total recording time were simulated by varying each of these factors in the original log of event times prior to breaking the data into “epochs.”

2.6 Visual-Evoked Potential Paradigm

Data are also discussed using the EEG waveforms elicited from a visual-evoked potential (VEP) paradigm, collected as part of an ongoing human research study. This task was chosen because it elicits a very well-characterized, stereotypical EEG response that is time locked to the occurrence of events. In this task, participants (three males, five females) sat comfortably in front of a computer monitor. A black fixation cross is centered on the screen and remains on through all presentations. On each trial, a visual stimulus appears in the center of the screen for 150 ms followed by 1640- to 2155-ms interstimulus intervals containing only the fixation cross. On 12% of the trials, the stimulus is a picture of an insurgent (rare), and on the other 88%, the stimulus is a U.S. Soldier (standard), both presented against a white background. Participants are instructed to press a response key after each stimulus. VEPs described here were calculated as the mean signal from all “standard” (U.S. Soldier) trials, after standard preprocessing (filtering, artifact rejection, baseline correction).

2.7 Correction Algorithm

We tested an algorithm that was developed to address both clock drift and stimulus timing jitter and designed to be relatively universal for any EEG system. It requires only that the system is able to receive a single binary pulse trigger input (as with the Quasar system) and a minimum trigger encoding accuracy of approximately ± 75 ms. The process relies on using a secondary log file generated by the STIM PC of all stimulus events; this log file ultimately contains the onset data of interest for a research study. The process contains two primary parts:

- *Synchronization Phase:* At the beginning of EEG data collection, the STIM PC sends a series of codes to the EEG system, consisting of the same value repeated 31 times, with alternated spacing of 200 and 300 ms between triggers. The onset of each pulse is recorded in a log file on the STIM PC as well as by the EEG system controlled by the DAQ PC.
 - *Alignment Phase:* After data collection, the onset times of the 31 codes recorded in the STIM log file are used as a predictor for the corresponding values in the online-encoded ACQ PC log file using linear regression. The intercept of the regression line is used to align the first event of the STIM PC log file, so that it can replace the original encoded (potentially high-jitter) values. Additionally, prior to replacement, the new onset times are multiplied by a known “drift factor,” which relates the two clocks of the STIM PC and EEG system; this factor can be derived from either the slope of the regression line calculated here or prior testing with longer-range time vectors (the method chosen for this report).
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3. Results and Discussion

3.1 Drift and Jitter Observed

For each EEG system, drift was calculated by comparing the trigger event times reported by the system with those reported by the E-Prime logfile (from the STIM PC). Specifically, linear regression was used to calculate the slope of the best-fit lines between the two sets of times, using the E-Prime logfile as a predictor of the EEG system time. This estimates, on average, how much one clock drifts relative to the other, per unit time. Additionally, we calculated the mean and standard deviation of the difference in reported trigger times across the 500 events and estimated the average variability (jitter) related to the trigger encoding system (table 1). Across the four systems tested, a wide range of drift and variance was observed. Quasar’s HMS headset showed almost no measurable drift, while that of the Emotiv Epoc exceeded 0.1%. A comparison of the two ABM measurements (representing before and after a firmware update) showed nearly a 10-fold difference in drift, and two times the improved variability, marking a sizeable improvement in precision. While the overall trial-to-trial variability was relatively small (<1 ms), the exception to this was the Emotiv Epoc, which reported event times that varied substantially (by several sample periods) from our verified timing on almost every trial.

Table 1. Timing drift and mean error for each EEG system

System Mfr	Drift (%)	Mean Error (ms)	Std. Dev. Error (+/- ms)	Sample Rate	Acq. S/W
ABM: A	0.027575	0.344689	0.479946	256	B-Alert 2.45
ABM: B	0.002565	0.032064	0.281587	256	B-Alert 2.45
Biosemi	0.001879	0.023484	0.109064	512	ActiView 6.05
Emotiv	0.106463	1.330787	55.705045	128	TestBench 1.5.0.3
Quasar	-0.000626	-0.007828	0.123526	240	Qstreamer 1.5.1046

3.2 Simulated Effects of Drift

Given the extent and range of drift and jitter observed, we sought to investigate the potential effects of these issues if not properly accounted for and the extent to which they may pose a true pragmatic problem for evoked-potential data. As an initial step, figure 1 shows the simulated effect of a range of hypothetical timing drift values, as well as those observed in these systems, applied to a simple square wave function.

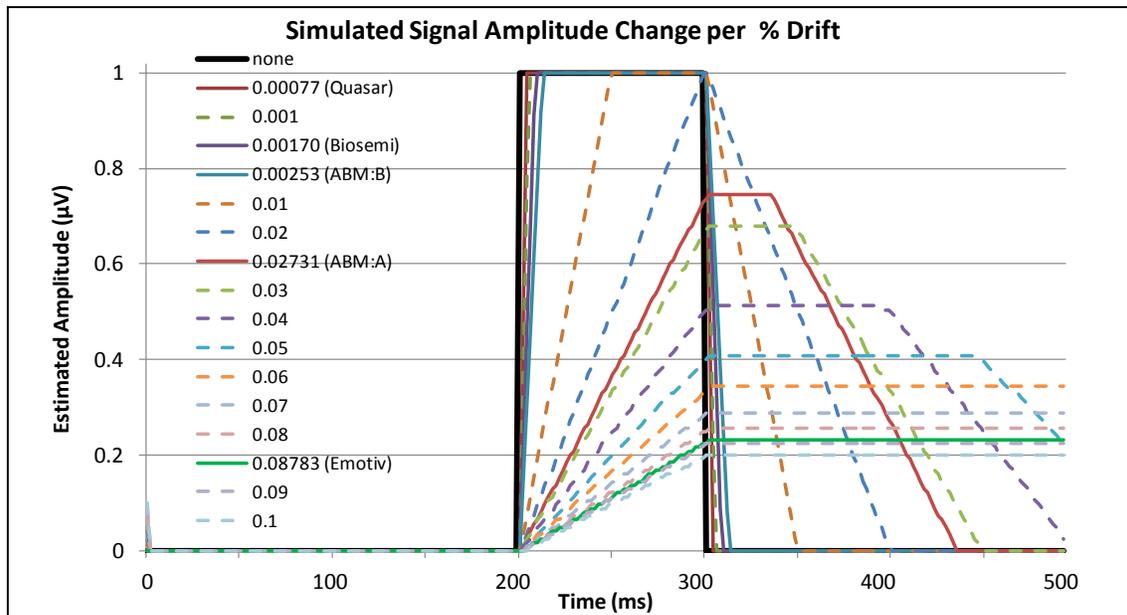


Figure 1. The simulated effect of a range of hypothetical timing drift values (dashed lines), as well as those observed in these systems (solid lines), applied to a simple square wave function consisting of 125 trials over 8.33 min.

This function represents a simulation of 125 “trials” with 4 s ISI, approximating an experimental recording session of 8.33 min, common for many behavioral experiments. As seen here, the overall effect is that of widening the base of the function while distorting the slope and suppressing the overall peak; the effect observed with the drift measured in the original ABM firmware (ABM: A, 0.0278) is a 12% decrease in amplitude and near doubling of base width, while the peak with Emotiv-simulated drift is suppressed by >76%.

Because this effect increases the difference in stated records over time (e.g., a progressive error), the extent of the effect increases as the length of recording increases. In order to depict the extent of this effect on typical recording times, figure 2 shows the effect of different total record lengths for two observed drift amounts: that observed with the ABM system originally (figure 2a) and after the provided firmware update (figure 2b).

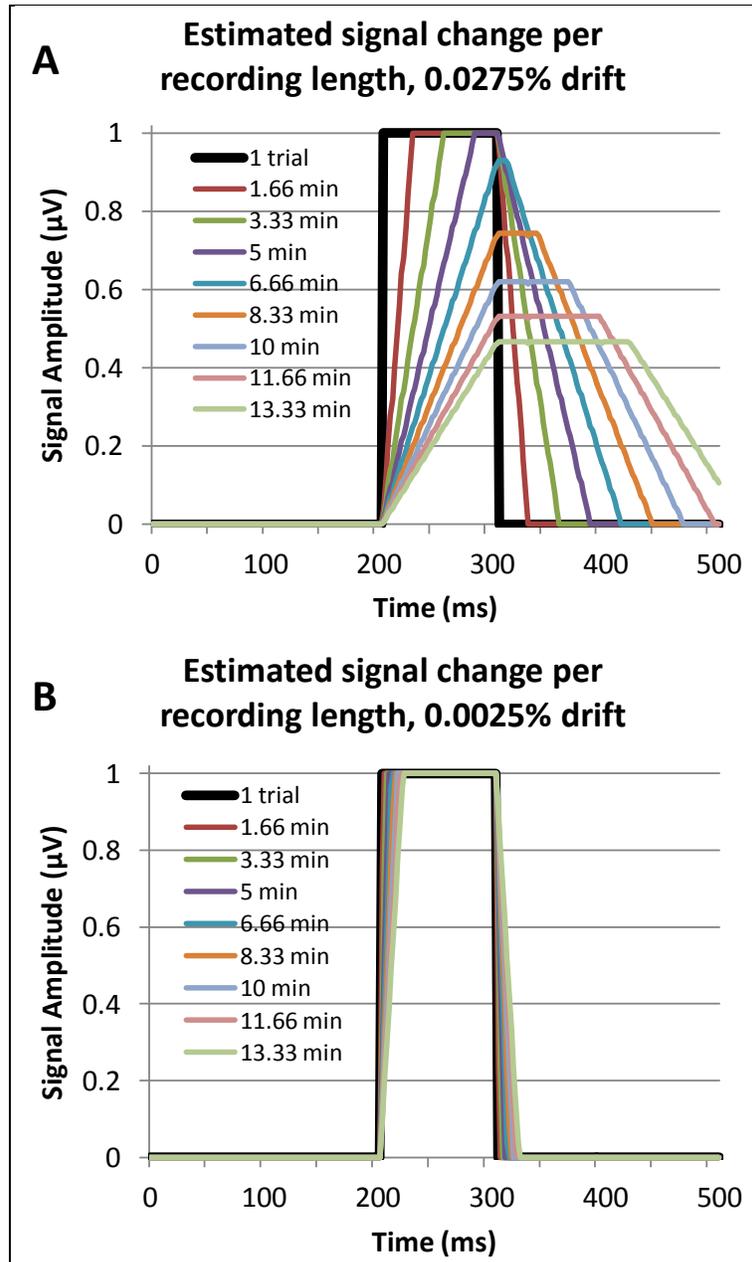


Figure 2. The effect of different total record lengths for two observed drift amounts from the two different ABM firmware versions.

With the larger amount of drift, a notable effect on the signal waveform occurs within only a few minutes of recording time. Meanwhile, if the drift is much smaller, the overall effect is relatively minimal.

While these data show the potential effect of drift, they are based on a static image with no intertrial variance or realism for human applications. Figure 3 shows scalp voltage event-related potential measured at channel Oz using the Biosemi system and confirmed correct, time-locked trigger event codes. As in figure 1, results are plotted using data with varied amounts of drift applied, including those measured in the EEG systems.

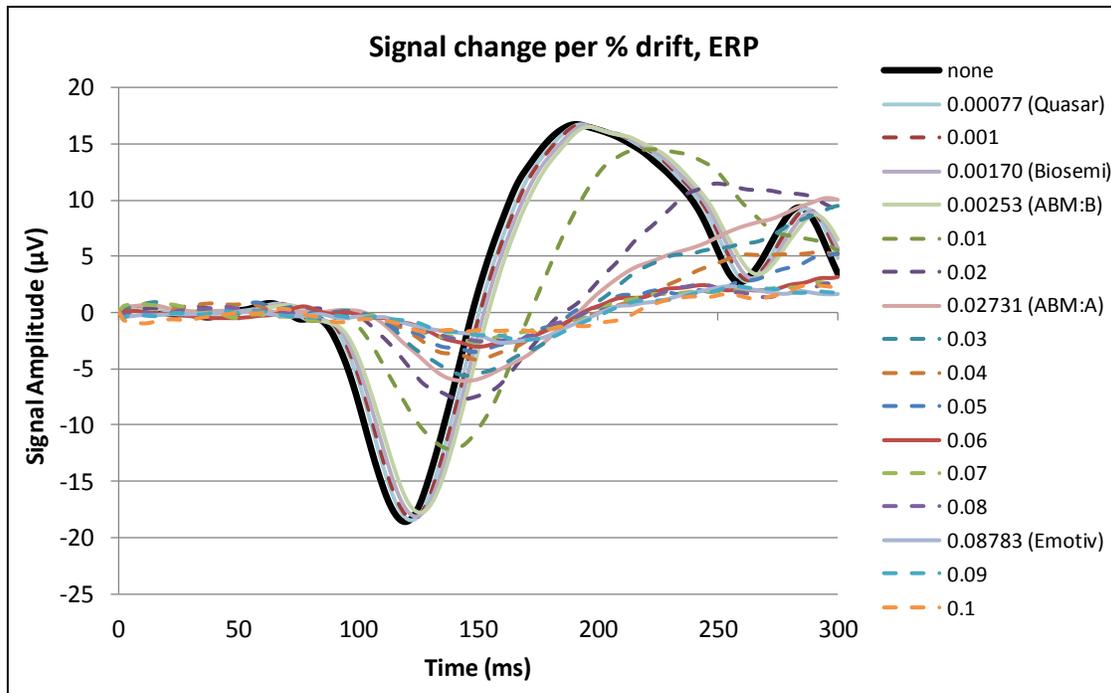


Figure 3. The simulated effect of timing drift applied to scalp voltage event-related potential measured at channel Oz using the Biosemi system and confirmed correct, time-locked trigger event codes. Data represent the response from a VEP task.

While the signal is only minimally distorted from the drift values observed with the Quasar, Biosemi, and updated ABM systems, application of a 0.01% drift dramatically attenuates the ERP peak, increases the latency, and widens the response slope. Meanwhile, this predicts substantial degradation if data from the original ABM firmware (ABM: A) or Emotiv do not account for drift, even to the extent that an ERP would be unrecognizable.

3.3 Simulated Effects of Jitter

The amount of jitter, measured here as variance in the difference between system-encoded and actual stimulus onset times, can also affect the clarity of a recorded signal. For three of the four systems investigated here, variability was relatively small—less than ± 1 ms around the mean

signal. Simulations of these amounts of jitter showed no noticeable effect on simulated or real ERP waveforms and are well below the scope of typical EEG systems.

In contrast, the Emotiv Epoc system displayed tremendous variance in the reported event times. Figure 4 shows the distribution of differences between actual and reported event times.

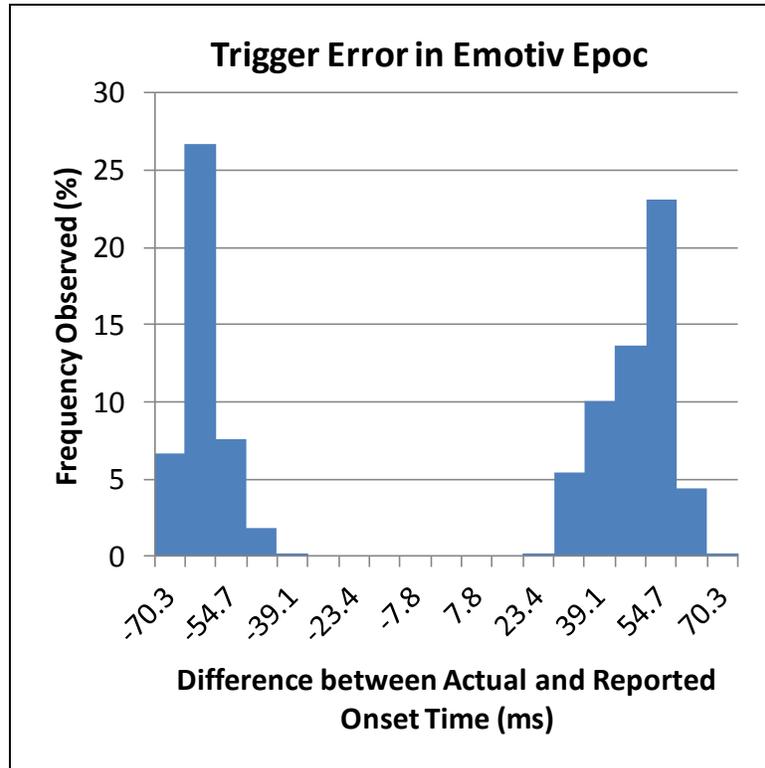


Figure 4. Distribution of recording errors (difference between actual and reported trigger onset time) measured with the Emotiv Epoc EEG headset.

Surprisingly, the system-reported times were never fully correct (e.g., 0-ms difference), but rather always either ahead or behind by several samples (1 sample length = ~ 7.3 ms) resulting in a bimodal distribution. To highlight how this extreme jitter likely affects recorded signal quality, figure 5 shows the effects of applying the difference values recorded onto the same square wave (figure 5a) and real human-derived ERP (5b) described previously.

That is, they illustrate how one might expect the signal derived from the Epoc-encoded stimulus timing to be affected solely based on the variability of that component of the system. Note that for a perfect signal, the amplitude is dramatically decreased and width nearly doubled, while for more realistic data (from human ERPs), the signal is nearly completely attenuated.

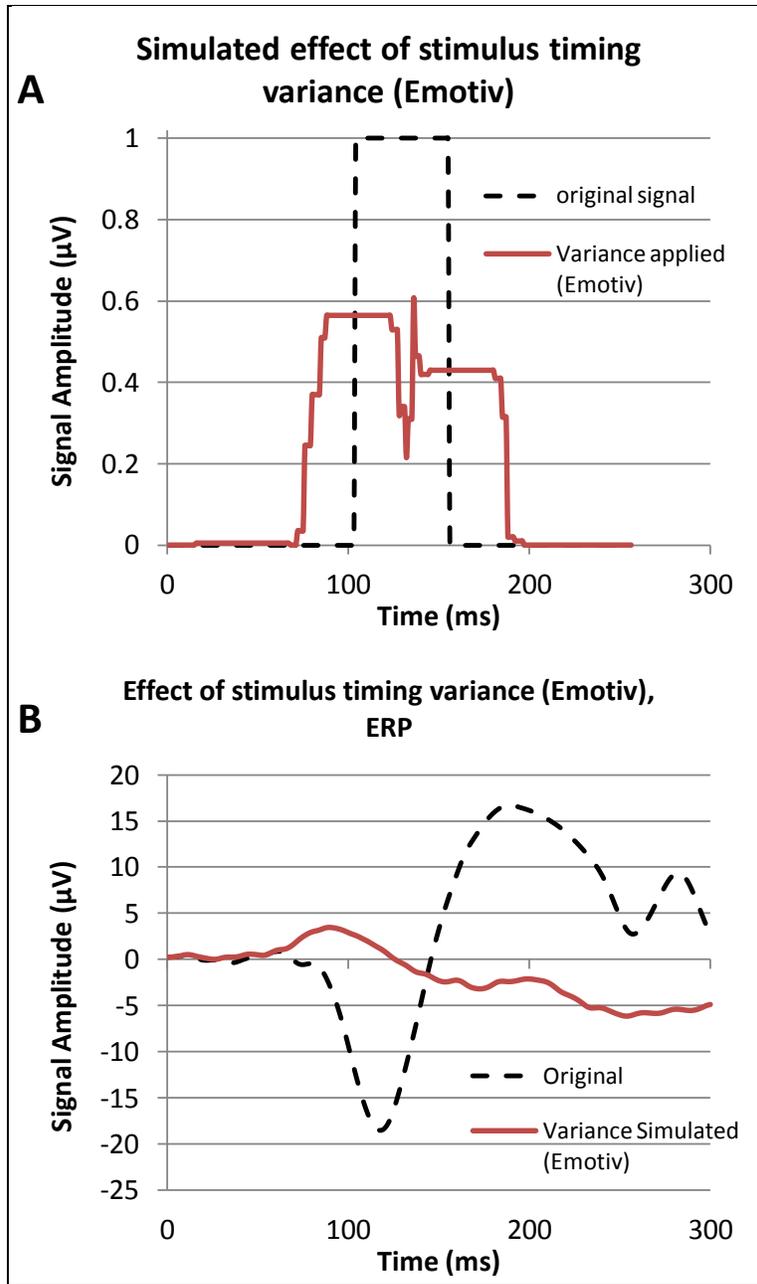


Figure 5. Simulation of the anticipated effects of the variance by applying the difference values recorded onto the same square wave (A) and real human-derived ERP (B).

3.4 Observations in Real Data (Phantom)

The results just outlined suggest that data recorded from the Emotiv Epoc system may be dramatically impacted by such large trigger encoding jitter. However, since these are based solely on simulating a single parameter, it is unclear whether this simulation truly encapsulates the real-world impact of data variance and drift. In order to fully estimate the overall quality of data that might be expected from this unit, we performed an additional session using a “phantom” head-shaped device. This device provides the opportunity to simulate the recording and processing of data just as from human subjects but with the advantage of providing a known-quantity original signal for the basis of comparison; this would not be possible from true human data or postrecording simulation.

Figure 6 shows data recorded using the Emotiv Epoc system in conjunction with the phantom head device. The input signal, a single 10-Hz sine wave, was programmed to occur in response to the stimulus paradigm for the VEP described previously. That is, a single 10-Hz wave was initiated at the onset of every trial, akin to an event-related response. Data were epoched based on external triggers encoded online using the vendor-provided software (TestBench 1.5.03) and processed identically to human-derived data described previously.

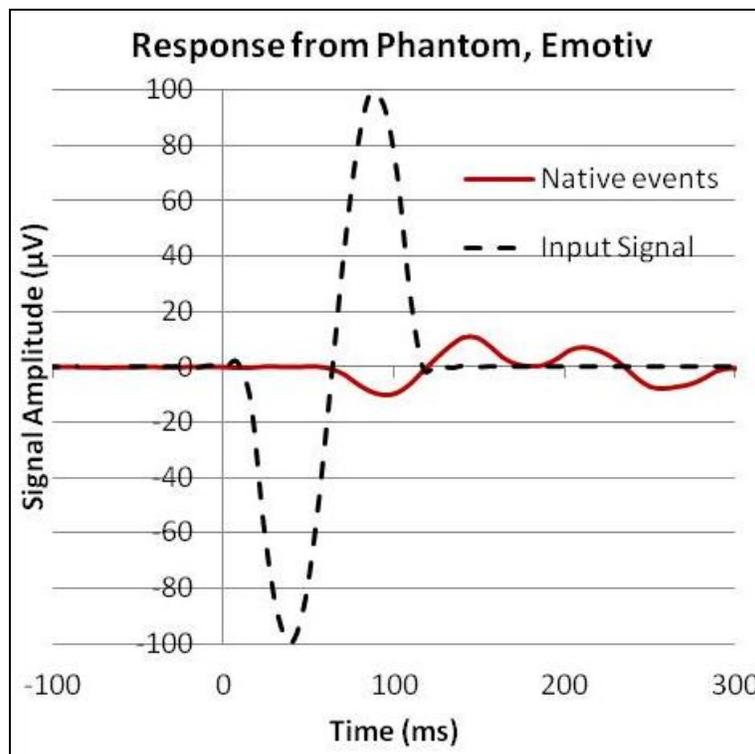


Figure 6. Data recorded using the Emotiv Epoc system in conjunction with a phantom head device. Natively reported data are shown in red.

Note that the recorded signal (solid red) is distorted, attenuated, and extended relative to the input (black, dashed) signal, most likely the effect of the varied timing. A fixed delay of just under 100 ms in the initial response was also observed.

3.5 Correcting for Timing Error

In order to compensate for the timing error described here (excessive encoding jitter and potential drift from referring to a secondary timing log), we have developed an algorithm that directly addresses both of these issues. The goal of this process is to draw on records from a second device with higher timing accuracy than the EEG system in question while ensuring that no drift-related error is introduced.

Figure 7 shows the results of applying this algorithm to the data from the Emotiv system recorded on the phantom device. Unlike the data derived from the natively encoded trigger times (red line, figure 6), the corrected signal (solid green) now closely resembles the original 10-Hz input function, without substantial distortion or widening of the overall form of the function. The additional negative deflection in the derived signal is likely an effect from the headset's automatic filtering.

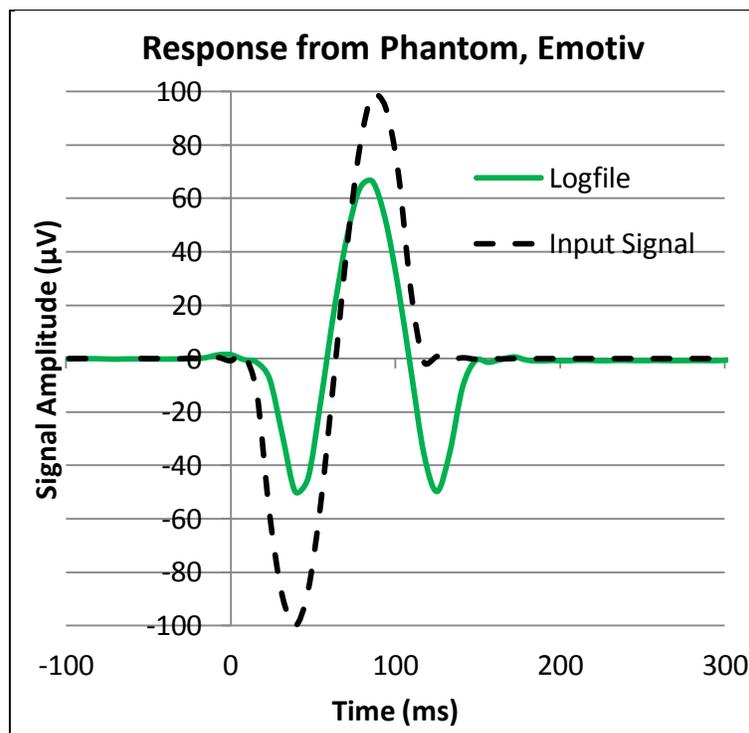


Figure 7. Results of applying a correction algorithm to the data from the Emotiv system.

The procedure was also applied to human VEP responses from the ABM (figure 8a) and Emotiv (5b) systems. Blue lines represent the original “native” waveform, red depict an example of imported data without adjusting for drift, and green show results using the compensation algorithm.

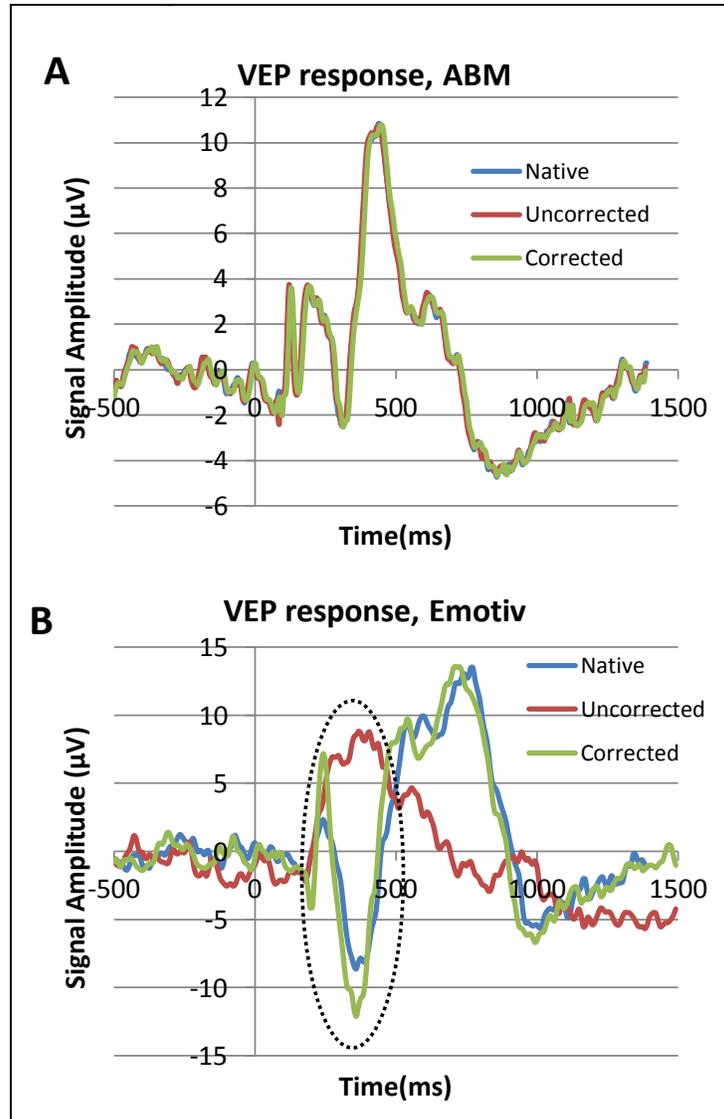


Figure 8. The same correction procedure applied to human VEP responses from the ABM (A) and Emotiv (B) systems.

Note that for ABM, which has relatively high timing precision and minimal drift, there is little need for, or effect of, correction. The signal based on the Emotiv system, in contrast, which has a substantially higher drift and variability rate, is noticeably improved using the procedure, especially within the early fast-phase response components (circled).

4. Discussion

Here, we have quantified the amount of drift and stimulus-encoding jitter that occurs within several contemporary, commercially available EEG systems, and shown the implications for the analysis of typical event-related potentials. We have found a wide range of both drift and encoding jitter, running the gambit from barely measurable (and likely trivial, e.g., Quasar or Biosemi) to fairly substantial (e.g., Emotiv and ABM's early firmware). Overall, we have shown that if timing drift is not accounted for, the effect on data averaging could be potentially problematic. This concern increases with longer recording times, especially those going beyond 8–10 min on a single record. The extent of this problem relies heavily on the total average drift of the system; when the drift is small, the potential effect is minimal, unless the recording time is excessive (e.g., >30 min). However, data derived from systems showing ~0.01% drift or more are altered catastrophically if this is not accounted for and thus must be of concern to users.

We include data here from one system (ABM's X-10 unit) using two different firmware versions: one originally supplied with the unit and an updated version supplied to us by the vendor. In this case, a near 10-fold improvement was measured in the overall drift, and 2-fold improvement in encoding jitter. Note that this (as highlighted in figures 1–3) had a fairly dramatic impact on the ability to properly estimate a native signal, due only to a fairly simple software patch. This improvement arose directly from feedback and discussion with ABM personnel, highlighting the benefits gained from vendor/lab interaction.

Of the four systems evaluated here, three are “wireless” (meaning no physical tether between the subject and DAQ PC) and newly (within recent years) released systems. In contrast, the Biosemi ActivTwo system, which relies on a physical connection to the recording PC, has been in wide use for several years and is often considered the “gold standard” of laboratory EEG. While the use of wireless transmission may raise the question of additional synchronization problems (such as from dropped packets or temporary data loss), no evidence of decreased performance in the realm of timing drift and jitter was seen here. In fact, the lowest drift observed occurred with the Quasar unit, which had timing variance comparable to Biosemi's system.

The Emotiv Epoc system showed significantly more drift and encoding jitter than the other systems tested. While this causes concern, a few caveats should be noted related to these inaccuracies. First, all other systems tested here (as well as most conventional EEG systems) use a direct input into the EEG system's DAC, typically coming from the STIM PC parallel port. The Epoc, in contrast, has no external input, and for third-party external triggering relies on input directly to the ACQ PC controlling the device and thus must be handled within software on that PC instead. Additionally, TestBench (the software provided by the vendor) provides only input via serial port. While the data transmission rate is very fast (recorded here at 56 kbps), communication access is only through the Windows buffer, which creates delays and

inaccuracies. Thus, it is very possible that the extreme jitter observed here arises simply from the trigger acquisition method and is not native to the device itself. Second, the retail cost of the Emotiv Epoc is currently only \$700 (for the research edition), a small fraction of the cost for any of the other systems (which are in the tens of thousands of dollars). Given this price point, it is unclear whether this unit, which is targeted for the consumer market, should even be expected to perform comparably. Finally, the sales team at Emotiv Systems is very clear that their target application does not focus on averaged evoked potentials. Nevertheless, we have been in continual contact with their technical team, who are aware of the degree of our results, acknowledged the problem, and requested continual feedback. Currently, they have provided a Beta version of TestBench, which we have tested, and observed an approximate 50% decrease in overall variance and drift. However, since this version has not been officially released to the public as of the time of this report, we did not feel it was appropriate for the review published here. Based on our interactions, we are hopeful of improved timing in the near future. Regardless of these concerns, however, we have also shown that using an additional synchronization and compensation algorithm can overcome these errors and provide a fairly robust signal.

5. Conclusions

In summary, we have shown that a wide range of timing drift and variance occurs across different EEG systems relative to a standard system clock. Depending on the extent of drift that occurs, it could be potentially catastrophic for averaged evoked potential analyses and thus must be monitored carefully. In cases where secondary data files must be referenced, lab personnel should consider using an additional synchronization algorithm, which we have shown to properly compensate for drift-related errors. In addition, use of such an algorithm can even improve the data quality from a system that may be otherwise questionable.

6. Recommendations

The detrimental effects of timing drift discussed here are a potential problem only under certain circumstances—specifically, when a second device is used to provide a log of event times. An example would be when a researcher refers to a log file created by the PC that provides stimuli to a subject, or logged data by an additional device such as an eye tracker, electrocardiogram device, or motion capture system. However, if data analysis relies solely on trigger information recorded natively by the EEG system online, then signal drift will not be a concern. Additionally, as shown here, it is only a concern if either the native drift of the system is sizably large (e.g., $>0.01\%$) or the data records being analyzed are extremely lengthy in time. That is, it

would not likely be a concern with Quasar HMS-system derived data, as it has natively almost no measurable drift.

Our primary recommendation is that researchers should quantify the drift expected for the system they use, similar to the methods described here. This will serve two purposes. First, it will identify the degree to which this issue must be addressed in the future. Second, the data will provide the researcher with a quantified “drift factor,” which can be used for correction algorithms later if necessary.

For those concerned about ensuring that drift does not adversely affect average ERP analyses, we recommend choosing among the following approaches:

1. *Rely Solely on Embedded Triggers.* Trigger data encoded by the EEG system online received from a secondary source are very unlikely to show drift. This is accomplished either through a direct cable connection (if using a second PC) or online software communication, such as TCP protocols. However, it is not always possible to predict all of the event information that may be desired to align with the EEG prior to beginning a study. Additionally, hardware limitations may limit what can be embedded during acquisition. For example, the Quasar HMS system provides only a single binary TTL input for external triggers. As a result, the native data contains only trigger onset times and does not have the ability to encode different types of stimuli; a second data file must be referenced to extract this information.
2. *Use Third-Party Synchronization Software at Acquisition Time.* Some available software packages are designed specifically for recording information from different physical and/or virtual sources (e.g., an EEG system, motion capture device, and presentation software). They create a central “clock” to which all other activities are logged in reference, so that data streams are inherently synchronized, even when data sample rates may be asynchronous. Some examples are Data River (Shwartz Center for Computational Neuroscience, University of California at San Diego), MAPPs (EyesDX; Coralville, IA), and BCI2000 (Wadsworth Center of the New York State Department of Health in Albany, New York). By using a central clock and encoding from all devices at run time, these dramatically reduce the opportunities for drift-related error. Note, however, that use of these software systems requires them to already support all devices/programs a researcher intends to use, otherwise the scientist must work with the developers to build additional devices into the data stream.
3. *Use Embedded Triggers and a Synchronization Algorithm To Align Files Off-Line.* This is the method briefly described in this report. In summary, a series of trigger tags sent from the presentation software are embedded in the EEG data online and recorded with time stamps in a separate log file, along with any supplemental event information. Trigger onsets between the two files (native EEG and stimulus file) are compared and synchronized using regression or other compensation algorithms, and the EEG-aligned event markers are

modified appropriately. This approach requires planning at least the synchronizing pulses prior to run time and assessing the system drift. However, it alleviates the need for development from a third-party vendor while allowing the option of referring to data not acquired at run time. Additionally, we have shown here that in the event that the stimulus-data recording equipment has higher fidelity than the EEG system, this method can even increase the overall accuracy of the reported waveform (as evidenced here using the Emotiv Epoc system).

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