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SPECIAL ISSUE

Basic Concepts of Surface Electroencephalography and Signal Processing as Applied to the Practice of Biofeedback

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The principal challenges involved with recording and analyzing surface electroencephalography (EEG) are presented in a way that is clear for the nontechnical reader. The influence of interpatient variability, signal acquisition techniques, and general effects of digital signal processing are described. A signal-processing example using surface EEG data is presented, and recommendations are proposed with the goal of increasing reliability and achieving better clinical outcomes when working with surface EEG.

The practice of neurofeedback requires knowledge in such varied areas as psychology, neurophysiology, electroencephalography (EEG), and digital signal processing. Often, an understanding of neurophysiology and complex signal processing is required to use the many tools available, which can be daunting at times for the nontechnical practitioner. Also, several factors that can reduce reliability are present when recording and processing EEG, which makes it difficult to compare results across recorded sessions and, even more importantly, across subjects. Thankfully, there exist some basic guidelines that, when followed, can help to remove the influence of these factors as much as possible, make things a little easier, and hopefully lead to better clinical outcomes.

Neurophysiology

The acronym *EEG* is short for *electroencephalography*, which is the capture and display of the electrical activity of the brain. More precisely, it is a measure of the electrical field produced by a large number of synchronously active neurons, as a function of time. This electrical field can be measured using electrodes either on the surface of the scalp or surgically implanted in the brain. Clearly, for the purpose of neurofeedback, surface electrodes are the only alternative (unless you are ready to dabble in neurosurgery!).

The EEG signal measured at the surface of the scalp occurs as a result of pyramidal neuron activity in the cerebral cortex (Marieb & Mallet, 1997; Nunez, 1981). The electrical communication along the cell itself is in the form of a primary current, which in turn sets up secondary currents of ionic charges in the extracellular fluid, circling to restore ionic concentrations. The net effect of these currents acts as a current source perpendicular to the surface of the cortex. The direction of the flow of current of this source is shown as a blue upward-pointing arrow in Figure 1a. Although they may be located within the same region of cortex, because of the heavily convoluted nature of this tissue, the orientations of these current sources differ completely, as seen in Figure 1b. A current source produces an electrical field (an energy field that influences charges in its vicinity, analogous to how a magnet affects metallic objects), the orientation of which is dictated by that of the current source. The electric field measured at the surface of the scalp is due to tens of thousands of synchronously active cortical neurons (Baillet, Mosher, & Leahy, 2001; Nunez, 1981; Vander, Sherman, & Luciano, 1994) and is therefore a heavily tangled web of electrical energy. A somewhat vague graphical depiction of this is shown in Figure 1c.

Surface EEG represents "only a fraction of the activity of the brain" (Neidermeyer & Lopes da Silva, 2005). The signal captured is mostly cortical activity, but the origin of that activity can be the cortex itself or a deeper structure; the current then will have travelled via neuronal propagation (the means by which neurons communicate with each other) and passive volume conduction (a complex phenomenon through which electrical signals travel through brain tissue). For example, visual processing occurs in the occipital lobe of the cerebral cortex, whereas complex mental acts such as language processing and memory tasks occur as a result of a network of cortical and subcortical nuclei originating in the deeper structures (Vander et al., 1994). When the activity has travelled from a more internal source via neuronal propagation, it is unknown whether it has been altered, and if so, by how much, by the time it propagates to the cortex (Neidermeyer & Lopes da Silva, 2005).

The concept of volume conduction carries important implications. The two underlying principles of volume conduction that apply to surface EEG are (a) currents are not restricted to the immediate neighborhood of the source, or generator (although they are often densest there), and (b) the electrical activity measured between two electrodes has more to do with their orientation than with the proximity of the electrodes to the generator. To understand the first concept, imagine how the heart signal can appear as an artifact in an EEG recording. Clearly, currents generated in the heart tissue flow through the head and register significant potentials, even at such considerable distances from the generator (Gloor, 1985). The second concept implies that the orientation of the generators shown in Figure 1b has important consequences for the signals we measure and the placement of the electrodes on the surface of the scalp.

The impedance of all the anatomical components of the head, between the brain and the sensing electrode, influence the signal significantly as well by imposing an unknown amount of attenuation and waveform distortion. Coupled with the ever-present interpatient variability that complicates all EEG research and clinical work (as no two brains produce quite the same EEG and no two skulls impede the signal in quite the same way), this acts as yet another source of ambiguity in the surface EEG signal.

Practically speaking, these physiological factors have always been present in the recording of surface EEG and are by no means detrimental to the practice of EEG biofeedback. They simply provide a challenge that must be met with careful procedures and diligent scientific method such that their influence may be reduced as much as possible.

Signal Acquisition

Surface EEG is recorded using biopotential electrodes fixed to the scalp. Important standards and guidelines involving site localization and electrode placement have been implemented to ensure signal integrity and repeatability in recordings (American Clinical Neurophysiology Society, 1994; Jasper, 1958). Electrode placement guidelines are therefore a good place to start increasing reliability, and they should be followed with the same careful attention every time surface EEG is recorded.

Biosignal amplifiers are most often differential amplifiers, to benefit from what is known as common mode rejection between electrode pairs (Webster, 1998). This means that whatever electrical activity is common to both sites is rejected, and what differs is amplified and processed by the computer. This is designed to reduce noise by assuming that what is common to both sites is exogenous artifact and what differs between both is EEG activity. For a given electrode pair, if one electrode is placed on a site that is relatively EEG neutral, meaning that negligible or no EEG activity should, in theory, exist there (e.g., the earlobe or mastoid process of the skull), then what is captured is considered to be the EEG present at the site of the other electrode in the pair. (In reality, the search for the perfectly quiet reference on the head or nearby, where no EEG activity exists, is yet another challenge.)

The difference between monopolar and bipolar montage is easier to understand when relating it to this explanation of differential amplifiers. Recall that in both cases, whether recording with bipolar or monopolar placement, the amplifier is capturing the difference between the respective activity at each site. Both are in fact bipolar recordings, in the sense that there are two inputs to the amplifier. When the second electrode is placed on an EEG neutral site, the recording is considered monopolar (or referential), because only one site is believed to be capturing EEG. When both electrodes are placed over sites that capture active EEG, the recording is called bipolar (also called sequential or differential).

There are three main reasons monopolar recordings are recommended for surface EEG recordings. The first is that because the differential amplifier rejects everything that is common to both electrodes, it will reject any common EEG activity, which is far less present in monopolar recordings. The second reason is that a bipolar recording can be derived from a monopolar one using simple arithmetic, whereas the opposite is impossible: A bipolar recording can never be transformed into a monopolar one. The third reason was hinted at in the description of volume conduction theory above. The principles of volume conduction tell us that with monopolar placement, we can at least lend partial justification to the notion that the electrode with the largest amplitude is likely closest to the generator, although this concept is simply inapplicable to bipolar recordings (Gloor, 1985).

In essence, there is more information and less distortion in the monopolar recording, so it is logical to consider it a more suitable strategy for acquisition (Fehmi & Collura, 2007; Fehmi & Sundor, 1989). For analysis, there are benefits to viewing the recorded data using both monopolar and bipolar montages, as switching back and forth between the two can reveal many clues, as to, for example, generator locations or event classification. This is possible only when recording with monopolar placement and is most beneficial when a full set of electrodes is used (usually 19–32 channels, using the 10-20 placement standard).

To summarize the above effects of interpatient variability and electrode placement, Neidermayer and Lopes Da Silva (2005) stated the following:

The passage of the cortical EEG signal through leptomeninges, cerebrospinal fluid, dura mater, bone, galea, and scalp has a strongly attenuating effect on the original signal. . . . Precise determination of the voltage of each wave is unnecessary and should be discouraged as pseudo-accuracy, too many variables are involved (above all, the inter-electrode distance and the type of montage, whether bipolar or referential recording). Electroencephalographers may indicate in their reports a certain amplitude range, such as "alpha rhythm from 20-30 uV," or, even better, limit themselves to statements such as "of medium voltage" or "of low to medium voltage" (p. 168).

The understanding of this concept of absolute amplitude, on its own as well as in the context of digital signal processing, is critical to the use of surface EEG in any application.

Signal Processing

Without going into too much detail, it is important to point out that digital signal-processing methods alter signal characteristics in ways that are at times unpredictable. Although in many cases these effects are negligible either because they are insignificant in magnitude or because the end result is independent of them, there are also cases in which these effects can actually influence outcomes. It is not necessary to identify each and every one of these cases, but it is beneficial to follow general rules that can help avoid many of them altogether.

It is also important to understand the fundamental principle in the design of all engineering applications: Every decision involves a trade-off between a benefit and a cost. In other words, nothing comes for free. If improved accuracy is desired, for example, the price may be high processing times or more complex hardware. Where biosignal processing is concerned, in addition to these trade-offs comes the uncertainty associated with the biomedical signal itself. In the case of EEG, it can never be known how accurately the signal is being processed, because there is incomplete a priori knowledge of the intended result. Most often, a combination of precedence of innovative research, advances in the fields of medicine and signal processing, basic mathematical rules, and common sense are relied on, but the ideal recipe, so to speak, has yet to be found.

Leaving aside the consideration of technical specifications such as sampling rate, noise, A/D resolution, and so forth, software-based processing routines such as digital filtering, frequency transformations, and power analysis all come with a cost, and therefore, decisions must be made as to their exact use. Neurofeedback clinicians are often expected to understand the concepts of engineering tools and techniques, and this can cause quite a bit of confusion, which unfortunately leads to distrust and even controversy at times. As a general rule, the goal should be to reach clinical outcomes in the context of internal signal-processing parameters but without having to modify them. The following example involving digital filtering is used to illustrate this point.

In a simple test performed by the author, the same block of EEG data was filtered using four different filters (a Butterworth low pass at 20 Hz, an elliptical low pass at 20 Hz, an 8- to 12-Hz Butterworth band pass, and an 8- to 12-Hz elliptical band pass). Only the filter order was changed, and a measure related to the amplitude of the output signal was computed in each case. For each filter, the amount of dependence on this simple change was estimated. (Note that in the text that follows, the term *variability* is used to describe the change in the amplitude measure due to the modification of the filter order and can be considered as contributing to a reduction in reliability.)

Figure 2 shows the raw EEG (panel a) and the output of each of the 8- to 12-Hz Butterworth filters (panel b). Variations in output amplitude are visible between each filter, the most significant of which reaches more than 6 microvolts, as shown by the red arrow in Figure 2b. This may be due to the slight variations in bandwidth introduced by the change in filter order, as in general, higher order provides more accurate bandwidth definition (Proakis & Manolakis, 1996).

The other important thing to note in Figure 2b is that the output delay is greater with increasing order. This is the cost associated with the benefit of better bandwidth definition. How much this affects the EEG being processed (in this example, alpha activity at 8–12 Hz) is unclear, and the question naturally arises as to how accurate the bandwidth should be.

Similar data for all four filters are presented in Table 1. Of note are the even larger variations in the data from the elliptical filters. Elliptical filters offer more accurate bandwidth definition but introduce more phase distortion than the simpler Butterworth filters. As always, the choice depends on the application.

The same test was repeated, but instead of measuring absolute amplitude in the output, a measure of relative amplitude was used. This was achieved by taking the ratio of the amplitude measure in the same EEG block to the amplitude measure of a similar block located in time at the beginning of the recording. The results in Table 2 show a reduction in variability in all cases.

The reduction in dependence on the change of filter order between the relative and absolute cases is shown in Table 3. In the worst case, an improvement of 110 times in the variability can be achieved by using a measure related to the

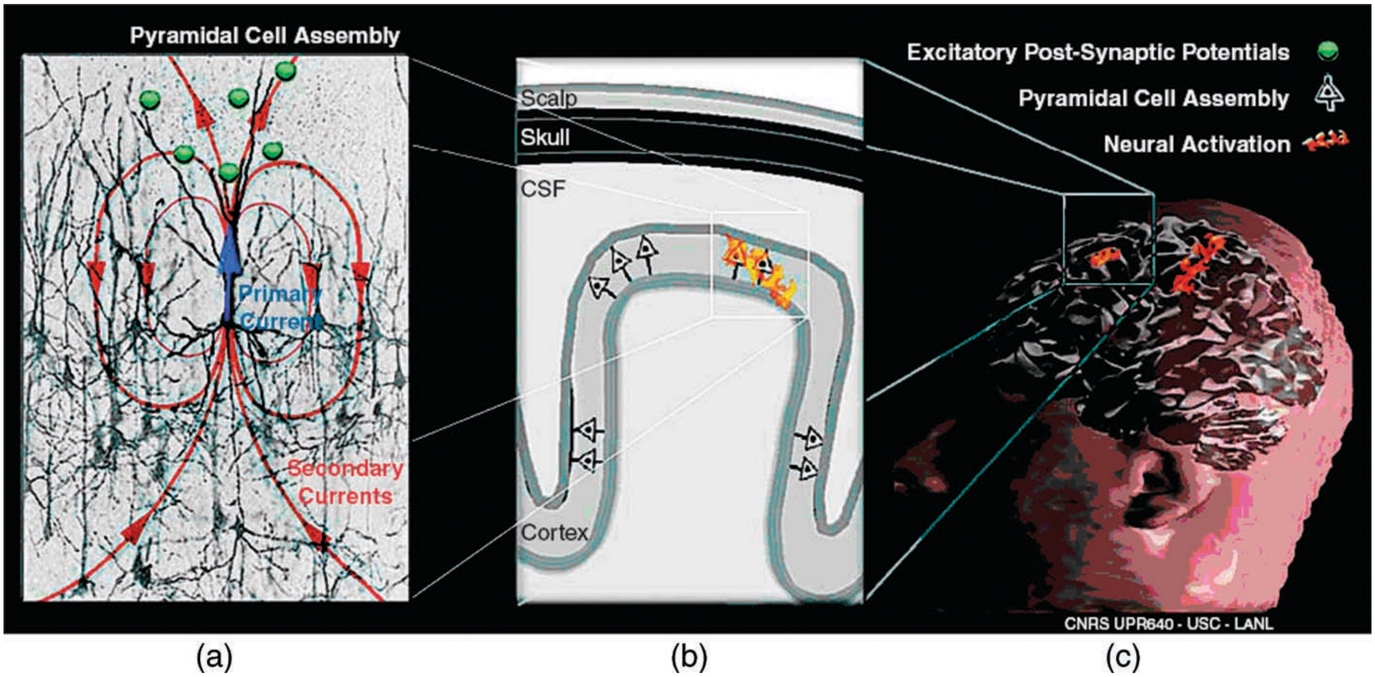

Figure 1. (a) Pyramidal neurons and the ionic currents that arise during communication. (b) Organization in the cerebral cortex. (c) Rendering of activity perceived at the surface of the scalp. Image taken from Baillet et al. (2001). Sponsorship for color figures provided by BrainMaster Technologies, Inc.

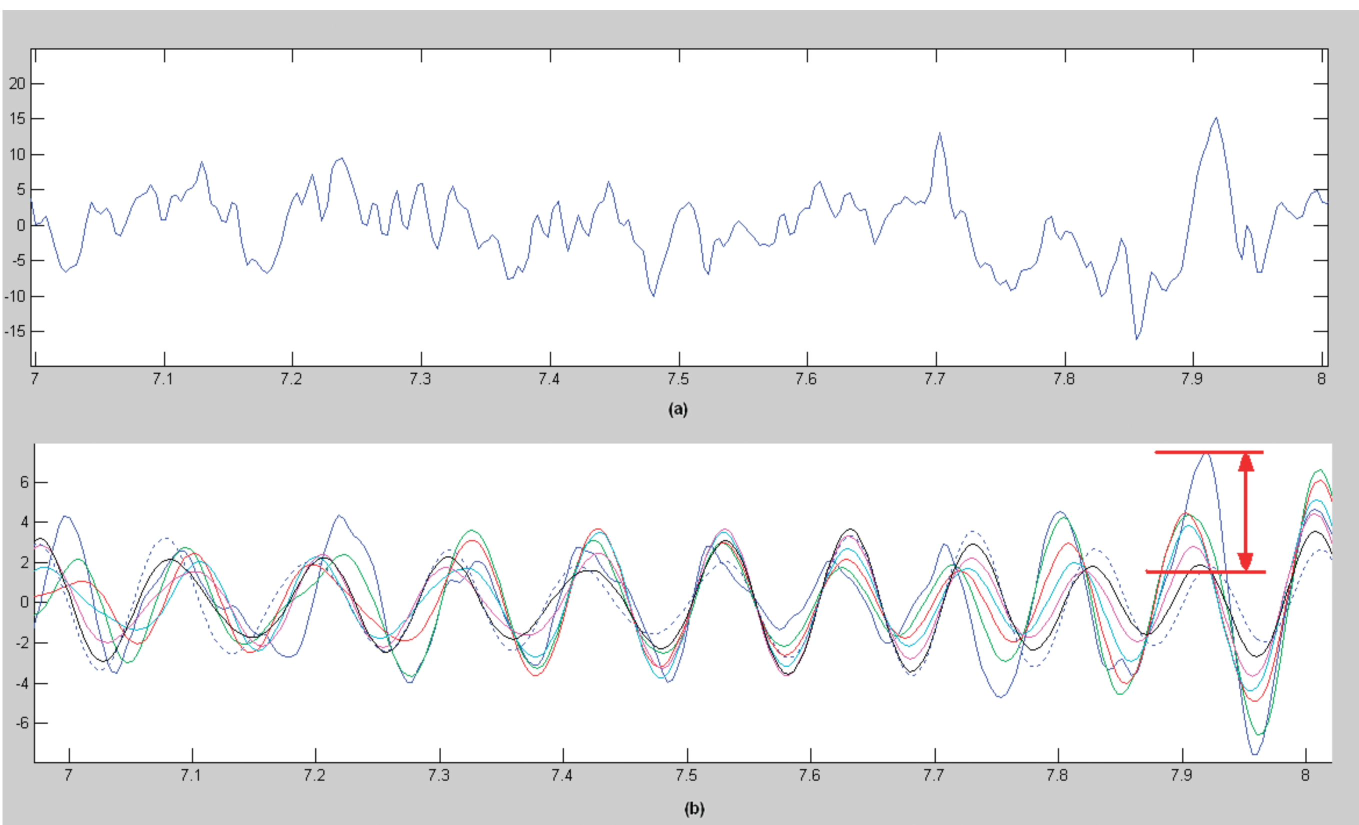

Figure 2. (a) One second of raw electroencephalography data. (b) Output of seven different 8- to 12-Hz Butterworth digital filters, ranging in order from 2 to 14. The important thing to note is that although they look very similar, the output delay increases with increasing order, the signal is distorted unpredictably in some cases, and more importantly, the amplitudes for each filter output vary (as much as 6 microvolts between certain cases, shown with red arrow). Colors are listed in order of increasing filter order: blue, green, red, cyan, magenta, black, blue dotted. Sponsorship for color figures provided by BrainMaster Technologies, Inc.

Table 1. Variability as a percentage of mean (absolute amplitudes)

	Butterworth		Elliptical	
	Std	Var	Std	Var
LPF	1.53	0.07	8.75	2.18
HPF	7.88	0.95	27.14	12.36

Note. LPF = low pass filter, HPF = high pass filter.

variance of relative amplitude over the variance of absolute amplitude.

Whatever measure is used to quantify variability, less variation will always be shown in the relative case than in the absolute case. This is simply due to the fact that in the relative case, both blocks of EEG are filtered with the same filter and are hence affected the same way. Although it is unclear how they are actually affected, by making relative measurements, this influence is eliminated. This is one consideration that might allow the comparison of results across sessions and even across patients, as it also serves to remove any other source of variation that is present in both blocks of EEG.

This is really a bit of an extreme example to prove a point: Rarely will it be recommended to use a filter of order 14 for EEG biofeedback applications. But it does show that output can be significantly influenced by simple parameter changes, the importance of which is often underestimated. Also, this is only one parameter and hence only one source of variability. As others are introduced in parallel, as they often are, the effect grows exponentially and increasingly randomly. If it is unclear what effects are being introduced into an experiment, the results can never really be fully understood. Conclusions must be made in the context of these unknown influences (at least by attempting to identify them, if eliminating them is not possible).

Summary of Recommendations

Pick your fruit: Compare apples to apples. Increase measurement repeatability as much as possible by using standard placement techniques and always using the same site for the reference electrode. Ensure that software settings are constant from session to session, and keep notes of all the settings employed for future reference (filter types and parameters, fast Fourier transform window types and lengths, electrode placements for active, reference and ground sites, sampling rate, equipment model numbers, etc.). Leave the difficult signal-processing decisions to the experts, or at the very least, avoid changing internal parameters unnecessarily.

Table 2. Variability as a percentage of mean (relative amplitudes)

	Butterworth		Elliptical	
	Std	Var	Std	Var
LPF	1.33	0.02	1.85	0.04
HPF	2.12	0.04	3.35	0.11

Note. LPF = low pass filter, HPF = high pass filter.

Table 3. Variability improvement factor of relative over absolute amplitudes

	Butterworth	Elliptical
LPF	3.40	55.80
HPF	22.43	110.56

Note. LPF = low pass filter, HPF = high pass filter.

Everything's relative. Limit the influence of interpatient variability, and increase the reliability in the signal processing and even in the equipment by using relative measures as much as possible (e.g., relative change, deviation from baseline, ratios, etc.). Absolute amplitude can be used for training, for example, upward or downward (which essentially is a relative concept), but should never be compared from one subject to the next or even from one session to the next. When judging the effects of modifying inputs to an experiment (physiological, technical, or otherwise), control for all other variables to eliminate their influence and to evaluate the effects of one variable at a time.

Don't sweat the small stuff. Base conclusions on broad, repeatable results and on clusters of data as opposed to specific values. Before making conclusions, test as many subjects as possible with as little exclusion criteria as possible.

No EEG is an island. Surface EEG is only one method of many to evaluate brain function. Consider including more information from other methods whenever possible.

Surface EEG is a fast, easy, and noninvasive tool to assess the brain's cortical function. Even with its ambiguities and imperfections, it remains a fantastic and very practical method of analysis as long as it is used in context of its shortcomings. The above recommendations may be followed in an attempt to simplify the use of surface EEG in biofeedback and to hopefully improve research and clinical outcomes in the future.

Note

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References

American Clinical Neurophysiology Society. (1994). Guideline 1: Minimum technical requirements for performing clinical electroencephalography. *Journal of Clinical Neurophysiology, 11*, 114–115.

Baillet, S., Mosher, J. C., & Leahy, R. M. (2001, November). Electromagnetic brain mapping. *IEEE Signal Processing Magazine*, 14–30.

Fehmi, L. G., & Collura, T. F. (2007). Effects of electrode placement upon EEG biofeedback training: The monopolar-bipolar controversy. *Journal of Neurotherapy, 11*(2), 45–63.

Fehmi, L. G., & Sundor, M. A. (1989). The effects of electrode placement upon EEG biofeedback training: The monopolar-bipolar controversy. *International Journal of PsychoSomatics, 36*(1–4), 23–33.

Gloor, P. (1985). Neuronal generators and the problem of localization in electroencephalography: Application of volume conductor theory to electroencephalography. *Journal of Clinical Neurophysiology, 2*, 327–354.

Jasper, H. H. (1958). The ten-twenty electrode system of the International Federation. *Electroencephalography and Clinical Neurophysiology, 10*, 370–375.

Marieb, E. N., & Mallat, J. (1997). *Human anatomy* (2nd ed.). New York: Benjamin Cummings.

Neidermeyer, E., & Lopes da Silva, F. (Eds.). (2005). *Electroencephalography: Basic principles, clinical applications and related fields* (5th ed.). Baltimore: Lippincott Williams and Wilkins.

Nunez, P. L. (1981). *Electric fields of the brain*. New York: Oxford.

Proakis, J. G., & Manolakis, D. (1996). *Digital signal processing* (3rd ed.). Englewood Cliffs, NJ: Prentice Hall.

Vander, A. J., Sherman, J. H., & Luciano, D. S. (1994). *Human physiology: The mechanisms of body function* (6th ed.). New York: McGraw Hill.

Webster, J. G. (Ed.). (1998). *Medical instrumentation: Application and design* (3rd ed.). New York: John Wiley and Sons.

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