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DATA PROCESSING AND SIGNAL EXTRACTION

Dealing with artifacts: The EOG contamination of the event-related brain potential

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Eye movements and blinks represent a major source of artifacts in the electroencephalogram (EEG) and event-related brain potentials (ERPs). The origin of this artifact is the large difference in potential that exists between the cornea and the retina. Eye movements and blinks produce shifts of the electric fields that propagate across the whole head and that can be several times larger than the activity generated by the brain. Ocular activity can be monitored by electrodes located near the eyes (electro-oculogram, or EOG). The electric fields associated with eye movements and blinks are somewhat different. The simplest procedure for dealing with ocular artifacts is to eliminate trials on which EOG activity is detected (rejection). However, this technique may result in data loss and biased data samples, especially when one is comparing clinical populations or tasks involving large amounts of eye movements. Another approach involves estimation and correction of the ocular artifact on the EEG and ERP traces. Several techniques have been proposed. Some of them are reviewed in the present paper. Issues related to the accuracy of the various techniques, as well as other advantages and limitations, are also discussed. Finally, general guidelines for how to deal with ocular artifacts are proposed.

The difference in electric potential between the front and the back of the eye generates a large dipole-like electric field (electro-oculogram, or EOG) that may interfere with the surface recording of the electrical activity of the brain (electroencephalogram, or EEG). If the EOG does not change over time, its effect on the EEG will be a constant. Since the EEG is measured as a change with respect to a baseline value, the effect of a constant EOG is null. Therefore, EOG contamination of the EEG trace occurs whenever the eyes move, or whenever the propagation of the EOG to the scalp electrodes varies over time. This type of contamination is labeled *EOG artifact*, *ocular artifact*, or *eye-movement artifact.*

The EOG artifact is of great significance in the registration of EEG and event-related brain potentials (ERPs). In fact, when measured at the scalp, especially at frontal locations close to the eyes, the EOG signal (several hundred microvolts in amplitude) can be several times larger than the brain-generated scalp potentials (typically, less than 50 μV). Eye movements and blinks (both of which are associated with large EOG artifacts) are very frequent and may occur during the performance of various tasks or as the result of certain types of stimulations. The frequency and size of EOG artifacts may vary, depending on the subject population and on the task requirements. This may result in systematic differences that can be confused with experimental EEG or ERP effects. For these reasons, the report of the 1977 committee on guidelines for publication of evoked potential and ERP data stated that "The possible contamination from eye movements should be a major concern to all EP [evoked potential] investigators, and the measures taken to deal with this problem should be considered in any published report" (Donchin et al., 1977, p. 5).

Some of the most significant methods for correcting the ocular artifact have been described in a paper published by Brunia et al. (1989), who also reported comparisons between the various methods. The purpose of the present paper is to provide a classification schema for the various methods used to deal with the EOG contamination of ERPs, including the work that has been carried out since the publication of the 1989 paper. However, understanding the issue of EOG contamination and the techniques used to deal with it is greatly facilitated by a thorough understanding of the way in which this artifact is generated. Therefore I will first describe the generation of the EOG and its propagation through the scalp.

Generation and Propagation of the EOG

Traditionally, the EOG has been attributed to the fact that the external surface of the cornea (at the front of the eye) is electrically charged with respect to the posterior surface of the retina (at the back of the eye). Therefore, each eyeball acts like a battery and generates an electric

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field that propagates across the whole surface of the head, including the scalp. Recently, some investigators (e.g., Berg, 1989) have argued, on the basis of dipole-localization methods, that the eye dipole is mostly due to polarization of the retina with little contribution by the cornea. However, a problem with these methods is the difficulty of modeling the complex anatomy and conductivity properties of the eye region. For this reason, I will adhere here to the traditional account of the eye dipole as due to corneal − retinal differences in potential. It should be noted that most of what is reviewed in this paper is not influenced much by whether or not the cornea makes a significant contribution to the eye dipole.

At some distance from the eyes, the electric field generated by each eyeball approximates a dipole field, whose amplitude is relatively constant. The effect of the eyeball dipole on a particular scalp electrode is determined by the following factors:

Changes in the orientation of the eyeball (i.e., eye movements). Eye movements may occur in any direction and can be considered as combinations of rotations over two angles (a vertical angle and a horizontal angle). Each of these two types of rotations will provide a different componential change to the electric field over the whole surface of the scalp. Vertical movements will produce major changes along a sagittal axis, whereas horizontal movements will produce major changes along a coronal axis. In most cases, the movements of the two eyes are conjugated, and the fields generated by the two dipoles associated with each eye are integrated in a relatively fixed fashion. However, in the case of changes of eye convergence (such as those required by changing the distance of the point at which the two eyes are fixating), the impact of the movement of each eye should be considered separately.

The location of the measurement points on the surface of the head. In general, the gradient in electric potential will be stronger at locations closer to the eyes (e.g., at frontal locations) than at distant locations (e.g., parietal or occipital locations). However, this will interact with the direction of the eye movements: Vertical eye movements will influence midline electrodes much more than lateral movements. Conversely, lateral electrodes may be disproportionately influenced by lateral eye movements with respect to vertical eye movements. It is important to remember that all measures of electric potentials are taken as differences between two points. Therefore, not only the location of the active electrode is important, but also that of the reference electrode.

Changes in the propagation of the electric field across the head. Given the high resistivity of the skull, the skin is a major conductive medium for EOG fields. For the most part, the conductive properties of the scalp skin are relatively constant over time (this may change under conditions of high heat or humidity). However, the eyelids present a special case, because their position with respect to the eyes is not fixed. Movements of the eyelids may influence the way in which the ocular electric field propagates to the scalp (Barry & Jones, 1965; Corby & Kopell, 1972; Matsuo, Peters, & Reilly, 1975; Overton & Shagass, 1969). As a consequence, blinks result in artifacts in the EEG trace. During blinks, eye movements may also occur. In addition, the propagation of the eye-movement–related potentials may differ for eye-open and eye-closed conditions (Gasser, Sroka, & Möcks, 1985). Furthermore, the relative involvement of eyelid movements may differ for voluntary as opposed to involuntary eye movements, as well as for upward as opposed to downward gaze shifts.

Several investigators have demonstrated that, within certain limits, the relative effects of eye movements on two sets of electrode pairs are approximately linear (Corby & Kopell, 1972; Hillyard & Galambos, 1972; Overton & Shagass, 1969). In other words, the ratio between the change in electric potential generated by horizontal and vertical eye movements at two different sets of scalp electrode pairs is approximately constant over a large range of eye movements. This is expressed by the following formula:

$$\Delta \mathrm{vEOG}_{ab} \approx k_{\mathrm{v}(ab/cd)}\, \Delta \mathrm{vEOG}_{cd}$$

and

$$\Delta \mathrm{hEOG}_{ab} \approx k_{\mathrm{h}(ab/cd)}\, \Delta \mathrm{hEOG}_{cd}, \qquad (1)$$

where ΔvEOG and ΔhEOG are the vertical and horizontal components of the EOG, and $k_{\mathrm{v}(ab/cd)}$ and $k_{\mathrm{h}(ab/cd)}$ are the ratios between the effects of ocular artifacts at electrode pairs *ab* and *cd*, for the vertical and horizontal components, respectively. Empirical research shows that this relationship holds relatively well for horizontal eye movements and, to some extent, for downward vertical eye movements (Corby & Kopell, 1972; Hillyard & Galambos, 1972; Overton & Shagass, 1969). For upward eye movements, $k_{\mathrm{v}(ab/cd)}$ varies somewhat, presumably as a consequence of the associated movement of the eyelid (Hillyard & Galambos, 1972), or because of eccentricity of the eye dipole with respect to the eyeball (Berg, 1989). However, when the movements are not too large, the departure from linearity can be ignored, at least at a first approximation. Empirical data, however, show that $k_{\mathrm{v}(ab/cd)}$ is systematically smaller for blinks than for eye movements (Corby & Kopell, 1972; Overton & Shagass, 1969). More recently, some investigators (Möcks, Gasser, & Sroka, 1989) have argued that the different propagation to scalp electrodes of potentials associated with eye movements and blinks is due to the complex nature of the eye movements associated with blinks. Furthermore, the formulation expressed above does not distinguish the independent contributions of the two eyes. This simplification can be considered valid only when the movements (and blinks) of the two eyes are conjugated. In most experimental situations, however, it is possible to control the location of the subject fixation (at least to some extent) and convergence is not a problem (see, e.g., van den Berg-Lenssen & Brunia, 1989). Furthermore, $k_{\mathrm{v}(ab/cd)}$ and $k_{\mathrm{h}(ab/cd)}$ depend on several physiological variables and are susceptible to change over time and across subjects.

The vertical and horizontal components of the EOG are orthogonal. Therefore, the following formula can be constructed:

$$\Delta \mathrm{vEOG}_{ab} + \Delta \mathrm{hEOG}_{ab} \approx k_{\mathrm{v}(ab/cd)}\, \Delta \mathrm{vEOG}_{cd} + k_{\mathrm{h}(ab/cd)}\, \Delta \mathrm{hEOG}_{cd}, \quad (2)$$

where separate $k_{\mathrm{v}(ab/cd)}$ and $k_{\mathrm{h}(ab/cd)}$ may be considered for eye movements and blinks.

Note that the left term of Equation 2 ($\Delta \mathrm{vEOG}_{ab} + \Delta \mathrm{hEOG}_{ab}$) is the EOG artifact measured at the electrode pair *ab*. Note also that the vertical and horizontal components of the EOG ($\Delta \mathrm{vEOG}_{cd}$ and $\Delta \mathrm{hEOG}_{cd}$) can be estimated separately by using two pairs of bipolar derivations. The vertical component can be estimated by using electrodes located above and below the eyes, and the horizontal component can be estimated by using electrodes located outside the outer canthus of each eye. Of course, these pairs of electrodes will pick up electrical activity generated by the brain, besides that generated by the eyes (Iacono & Lykken, 1981; Oster & Stern, 1980). However, since at locations close to the eyes the electric field generated by the eyeball dipole is several times larger than that generated by intracranial electrical activity, the contribution of the latter can be, in most cases, ignored, and the two bipolar derivations can be considered as valid measures of the EOG.

Most procedures used to deal with eye movements (with the exception of the rejection approach) are based on the idea that the EOG contamination of the EEG can be estimated on the basis of some independent estimate of the EOG, usually obtained by using some type of regressive methods, and subtracted from the data in order to provide an artifact-free recording. In other words, they depend on the validity of Equation 2, or of a similar equation.

The Rejection Technique

The *rejection technique* is still one of the most common methods for dealing with EOG contamination. It involves discarding from the analysis epochs in which ocular artifacts are deemed to occur. This is often combined with instructions to subjects to refrain from moving their eyes or to blink during the recording periods.

A critical step in the rejection technique is the identification of trials in which artifacts occur. This may be done either by visually inspecting individual records or by setting some automatic detection criterion (e.g., activity exceeding 50 μV with respect to a baseline value). The detection of artifacts can be made on line (i.e., during the recording session) or off line (i.e., after the recording session has terminated). The advantage of on-line detection is that (at least in some experiments) additional records can be obtained to compensate for those lost due to artifacts. This, of course, can only be done when no significant consequence of repeating trials is expected.

The rejection technique is very simple and intuitive, and it does not require complex computation. It has several disadvantages, however. The first is that it may lead to a substantial loss of data, especially when one is testing children or subjects from clinical populations. A second disadvantage is that it may make it impossible to run experiments in which eye movements or blinks are an essential part of the task, such as experiments involving tracking of objects on a CRT screen or studying the ERP correlates of the blink reflex. A third disadvantage is that the sample of trials that are artifact-free may not be representative of the entire population of trials (i.e., there may be a selection bias). This can be a problem particularly when the conditions and/or subject populations that are compared may have a different frequency of eye movements or blinks (see, e.g., Andresen, Seifert, Lammers, & Thom, 1988; Gasser, Ziegler, & Gattaz, 1992). In some extreme cases, application of the rejection technique may lead one to discard all the trials for a subject or an experimental condition.

There are two more problems with the rejection technique. The first is related to the selection of an appropriate criterion for artifact detection (van den Berg-Lenssen & Brunia, 1989). Clearly, this criterion must be sufficiently sensitive to eliminate all trials in which artifacts occur. However, it must also be high enough to avoid "false alarms" and an excessive loss of data. While an optimal criterion that rejects all artifact-contaminated records and retains all artifact-free records can be obtained with "discrete" events, such as blinks, it is much more difficult to establish such a criterion for eye movements, which can vary in amplitude from very small to very large. Thus, the objective of completely eliminating any EOG contamination of the EEG may be, at least in some cases, impossible to obtain with the rejection technique.

The second problem is related to the associated instructions to refrain from blinking. These instructions, which are commonly given in EEG and ERP experiments, may actually introduce an additional task for the subjects. This "secondary" task may interfere with the brain processes that are under study. Indeed, Verleger (1991) showed that "refraining-from-blinking" instructions lead to changes in the amplitude of some evoked potentials (N1 and P3). In addition, since the frequency of blinks varies widely among subjects and conditions, the load imposed by the instructions may also be different (Wasman, Morehead, Lee, & Lowland, 1970), leading to a possible confounding of secondary task load with task or group effects. A similar problem may exist for instructions requiring subjects to "keep their eyes focused" (i.e., maintain fixation in the absence of a visual target).

EOG Correction Techniques

The disadvantages of the rejection technique have led several investigators to develop methods for correcting the EOG artifact from the EEG and ERP records without having to discard data. In general, these techniques are based on the following model:

$$\mathrm{oEEG}_{ab} = \mathrm{uEEG}_{ab} + \mathrm{vEOG}_{ab} + \mathrm{hEOG}_{ab}. \quad (3)$$

where the observed EEG value observed at a particular electrode pair (oEEG_{ab}) is considered as the sum of the uncontaminated EEG (uEEG_{ab}) and of the effects of the vertical and horizontal EOG artifacts at that particular electrode pair.

Combining Equations 2 and 3, one can derive the following general formula, used in most EOG correction techniques:

$$\mathrm{uEEG}_{ab} = \mathrm{oEEG}_{ab} - (k_{\mathrm{v}(ab/cd)}\,\mathrm{vEOG}_{cd} + k_{\mathrm{h}(ab/cd)}\,\mathrm{hEOG}_{cd}). \qquad (4)$$

In this formula, the estimation of the uncontaminated EEG is obtained by subtracting the EOG artifact, estimated by scaling the values of the vertical and horizontal EOG components recorded using dedicated electrodes. The various techniques differ from each other with respect to assumptions they make about the scaling factors and with respect to the procedure used to compute the scaling factors. Recently, Sadavisan and Dunn (1994, 1996) have proposed new techniques, based on a neural network approach and adaptive filter theory, which do not assume that the relationship between the EOG channels and the artifact observed on the EEG channel is linear. However, since the use of nonlinear approaches is at present very limited, I will not consider them further in this review.

Time Domain Techniques

Historically, time domain techniques were the first to be introduced. Time domain techniques are based on the assumption that the scaling factors ($k_{\mathrm{v}(ab/cd)}$ and $k_{\mathrm{h}(ab/cd)}$) are constant for all frequencies of EOG activity. They also assume that the propagation of the EOG artifact from the eyes to the rest of the scalp locations is practically instantaneous. Provided that this is the case, it should be possible to compute the scaling factors by using standard linear regression methods, or other similar statistical or mathematical methods. Several investigators have proposed methods based on this approach (e.g., Elbert, Lutzenberger, Rockstroh, & Birbaumer, 1985; Fortgens & de Bruin, 1983; Gasser, Sroka, & Möcks, 1986; Gratton, Coles, & Donchin, 1983; Jervis, Nichols, Allen, Hudson, & Johnson, 1985; Quilter, McGillivray, & Wadbrook, 1977; Verleger, Gasser, & Möcks, 1982).

The assumption of instantanteous propagation of the EOG artifact through the head is based on the notion that the eyeball electric field is electrostatic in nature. Some investigators have proposed that the head may conduct electrical activity differently, depending on the frequency (Gasser et al., 1985). In this case, the head might act as a filter, which might determine distortions of the shape of EOG activity depending on the location at which it is observed. However, other data support the idea that the impedance of head tissue is relatively constant across the range of frequencies under consideration (0.1–100 Hz) (Nunez, 1981). Further, whereas Gasser et al. (1986) reported a small delay (a few milliseconds) in the peak of EOG activity across electrodes, this was not replicated in subsequent work (see Berg, 1989; van den Berg-Lenssen, Brunia, & Blom, 1989). The issue of differential conductivity for EOG activity of different frequency has also implications for the assumption of a constant scaling factor across different EOG frequencies. Another reason for the observation of differences in the propagation of EOG potentials through the head as a function of frequency is that different EOG frequencies may carry signals related to different physiological phenomena. In particular, EOG potentials associated with blinks have very specific frequency characteristics, different from those of potentials associated with most eye movements. As mentioned earlier, blinks and eye-movement artifacts propagate to the scalp in different ways. This suggests that separate scaling factors should be used for EOG artifacts related to blinks and to eye movements.

Various time domain techniques differ in how the scaling factors are computed. For instance, Girton and Kamiya (1973; see also Fortgens & de Bruin, 1983) proposed computing the scaling factors by dividing the EOG record on scalp electrodes by that recorded on dedicated EOG electrodes in situations in which subjects were asked to make eye movements. These scaling factors were then used to correct the EEG data on line. This approach can actually be carried out in an analog fashion during the recording, by using appropriate electric circuits linking the EOG and EEG channels (Barlow & Remond, 1981; McCallum & Walter, 1968). A problem with most on-line methods is the requirement of calibration trials in which eye movements are made.

Regression methods were introduced by Quilter et al. (1977) and subsequently by Verleger et al. (1982), who proposed a regression method for estimating the scaling factors, in which only large EOG potentials are used for the computation. In the approach proposed by Verleger et al., the scaling factors are computed separately for each epoch and then averaged together.

Gratton et al. (1983) proposed a more elaborate time domain regression technique. This technique differed from the previous regression methods in two ways. First, separate scaling factors were computed for blink-related EOG activity and eye-movement–related EOG activity. This was made possible by a preliminary separation of data points in which blinks (detected by using a pattern recognition algorithm) occurred from the rest of the records. Second, the scaling factors were computed on the basis of EOG (and EEG) activity desynchronized with respect to stimulation (i.e., background activity). This was done to minimize the probability that noncausal temporal correspondence between EOG and EEG potentials would influence the computation of the scaling factor. This could occur if the stimulus, for instance, elicited both ERP activity (such as a P300, or an N400, or another ERP component) and EOG activity (such as a blink or an eye movement) that happen to occur systematically at the same latency. Although the original version of the procedure considered only one EOG channel (as did the techniques proposed by Quilter et al. [1977] and by Verleger et al. [1982]), Gratton and collaborators later introduced an expansion of their technique to be used with multiple EOG electrodes, based on a multiple regression method (Gratton & Coles, 1989; Miller, Gratton, & Yee, 1988).

Jervis, Ifeachor, and Coelho (1989; see also Ifeachor, Jervis, Morris, Allen, & Hudson, 1986; Jervis et al., 1985) also proposed a time domain method based on a multiple regression procedure. The major difference between Jervis et al.'s method and the other techniques reviewed earlier is an emphasis on using three EOG channels (one vertical and two horizontal, one for each eye) as predictors, and the use of iterative methods for the computation of the scaling factors. The use of additional EOG channels may facilitate the detection of radial components of the EOG (Elbert et al., 1985). The impact of radial components is also taken into consideration by the time domain procedures proposed by Elbert et al. and by Gasser et al. (1986; see also Möcks et al., 1989). Semlitsch, Anderer, Schuster, and Presslich (1986) also proposed a regression method in the time domain, in which eye-blink–related activity was used to reduce the influence of coherence between ERPs and EOG activity. Van den Berg-Lenssen et al. (1989) proposed another technique in which the scaling factors between the EOG and EEG channels are computed with the use of an autoregressive model of the EEG. The rationale for this approach is that it can account for a lag between the times at which the ocular artifact appears on the EOG and the EEG channel. It is unclear, however, whether this is actually useful, since the propagation of the ocular artifact through the head is practically instantaneous (Berg, 1989). A further innovative aspect of van den Berg-Lenssen's approach is the use of a maximum-likelihood instead of a least-squares procedure for the computation of the scaling factors.

Recently, Berg and Scherg (1994; see also Berg & Scherg, 1991; Lins, Picton, Berg, & Scherg, 1993) have modeled the EOG artifact by using a dipole-modeling approach. In this approach, the activity recorded at the scalp is modeled as the result of changes in the strength and orientation of a limited set of dipoles located in various brain and head regions. Within this context, two (or more) of the dipoles are located within the eyes. This modeling approach allows for the estimation of the eyeball dipoles' contribution to surface recordings, which can therefore be separated from the other types of brain activity. The procedure provides interesting insights into the nature of the ocular artifact and in particular shows the differential impact of upward and downward movements, as well as the differences between blinks and eye movements. This approach is computationally very demanding, however, and it is impractical for routine correction of EOG artifacts. In addition, the dipole-modeling procedure used depends heavily on assumptions about the propagation of electric potentials through the head that are hard to verify (but see Berg & Scherg, 1994). A particular problem is the difficulty of modeling the complex anatomy of the eye region as well as the impact of the eyelids.

Frequency Domain Techniques

Frequency domain techniques (e.g., Gasser et al., 1986; Möcks et al., 1989; van Driel, Woestenburg, & van Blokland-Vogelesang, 1989; Whitton, Lue, & Moldofsky, 1978; Woestenburg, Verbaten, & Slangen, 1983) are based on the assumption that the scaling factors depicting the propagation of the EOG field over the head vary with the frequency of the EOG activity. They can also in principle accommodate for differences between the phase of EOG effects at different electrode locations, but, as seen above, it is not clear that this is a significant advantage.

One of the major advantages of allowing for the scaling factors to vary as a function of frequency is the possibility of accounting for differences between blink and eye movement effects (as seen earlier, the technique proposed by Gratton et al. [1983] also allows this to be done in the time domain). Another advantage is that these techniques can deal better with slow drifts in potential during prolonged recording epochs, which are often a cause of inaccuracies in the correction of ocular artifacts with time domain methods (these drifts can be avoided by using short recording epochs or appropriate filtering procedures). A disadvantage of frequency domain methods is their higher computational cost (with respect to time domain methods). Among the models proposed so far, only that of Gasser et al. (1986) deals with the distinction between synchronous and asynchronous activity; the other methods can therefore be susceptible to inaccuracies due to spurious correlations between EOG and brain activity. A more serious problem is the possibility that low-amplitude/high-frequency EEG activity may contaminate the EOG power spectrum (Iacono & Lykken, 1981; Oster & Stern, 1980), which contains very little activity at high frequencies (above 5 Hz). This is not a significant problem for time domain methods, since the EOG signal is dominated by low frequencies, for which the EOG signal is several orders of magnitude larger than the EEG signal. However, in the case of frequency domain methods, the regression procedure would tend to inflate the correction factors at high frequencies artificially. For this reason, it may be necessary to filter the scaling function to suppress the values at high frequencies (see Möcks et al., 1989; see also van Driel et al., 1989).

Example of Application of an EOG Correction Method: The Gratton et al. (1983) Method

In this section, an example of application of a particular EOG correction method (Gratton et al., 1983; see also Gratton & Coles, 1989; Miller et al., 1988) will be presented. This method has been described earlier in this paper. Here I will show only how ERP waveforms contaminated by ocular artifacts can be "corrected" with this method; I make no claim about the significance of the results.

The data were obtained from 1 subject in a visual memory search paradigm. The stimulus was a character presented at the center of the display (foveal presentation), which, in the condition displayed in Figure 1, matched one of two stimuli presented some time earlier (positive test stimulus), although in other conditions it did not (negative test stimulus). ERP data were collected from 18 scalp electrodes (Fz, Cz, Pz, F7, F3, F4, F8, T3, C3, C4, T4, T5, P3, P4, T6, O1, O2, and right mastoid, RM) referenced to a left-mastoid electrode, using a .01–30 Hz band pass. The same band pass was used to record vertical EOG (with electrodes located above and below the right eye) and horizontal EOG (with electrodes located 2 cm outside the outer canthus of each eye). EOG was recorded bipolarly. A sampling rate of 200 Hz was used to record 240 samples beginning 100 msec before stimulus presentation. A total of 200 trials were recorded (the waveforms presented in Figure 1 refer to a condition which occurred in 35 trials). Trials with artifacts (defined as saturation of the A/D converter or as variations in amplitude exceeding 400 μV) were discarded before analysis. There were 10 such trials (5%). Ocular artifacts were corrected according to the procedure described by Gratton et al. (1983), expanded to include correction of both vertical and horizontal artifacts by means of a multiple regression method (based on the vertical and horizontal EOG channels as predictors for the ocular artifact on each EEG channel). As a reminder, this is an off-line time domain correction procedure which computes separate propagation factors for blinks and saccades (i.e., other types of eye movements) on the basis of the residuals in the EEG and EOG channels after subtraction of event-related activity on either channel.

The propagation factors computed for the entire experimental session are presented in Table 1. Note that the propagation factors decrease in absolute value from the front to the back of the head. Also, the propagation factors for the horizontal component of the EOG increase monotonically from negative to positive values as the location of the EEG electrode varies along a left to right direction. The horizontal EOG propagation factors are asymmetric, with larger absolute values on the right than on the left. This is due to the use of an asymmetric reference (left mastoid).

An example of the effect of correcting the EOG artifact on the data is displayed in Figure 1. In this figure, the average ERP waveforms from Fz before and after correction are displayed together with the average V-EOG. Note that the V-EOG indicates consistent activity beginning approximately 150 msec after stimulation. This occurred even though the experimental conditions did not require that the subjects make eye movements. To a large extent, the EOG activity is related to blinks unintentionally elicited by the test stimulus on a small proportion of the trials—although the stimulus used was of relatively low intensity and size. This activity partially overlaps the ERP activity, which, at the Fz electrode, also onsets approximately 150 msec after stimulation (although it appears to peak earlier than the EOG activity). After correction, the frontal ERP activity is reduced in amplitude and appears to return to baseline earlier (approximately 500 msec after stimulation) than in the raw data. The difference in amplitude between the Fz peak activity observed before and after correction is approximately 5 μV. This value is relatively large in comparison with the size of the effects obtained in the vast majority of ERP studies. This underscores the importance of dealing with EOG artifacts in ERP recording.

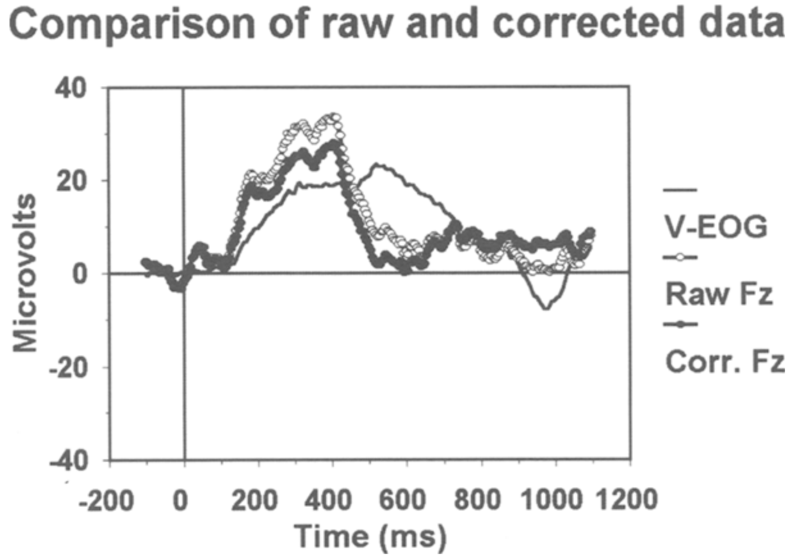

Figure 1. Average ERP waveform from Fz for 1 subject in a sample condition from a memory search experiment. ERP waveforms obtained without correcting for EOG artifacts (open circles) are compared with ERP waveforms in which EOG artifacts were corrected according to the procedure described by Gratton et al. (1983) (filled circles). The average V-EOG obtained in the same experimental condition is also shown (solid line).

Table 1
Propagation Factors in Example of Eye Movement Correction According to Gratton et al. (1983)

	Vertical		Horizontal	
	Blinks	Saccades	Blinks	Saccades
F7	.357	.345	−.252	−.125
T3	.064	.071	−.153	−.118
T5	.041	.055	−.104	−.003
F3	.284	.345	−.065	.124
C3	.100	.136	−.149	.064
P3	.053	.090	−.118	.056
O1	.034	.059	−.025	.100
Fz	.280	.311	.020	.230
Cz	.113	.155	.006	.190
Pz	.062	.108	−.054	.154
F4	.273	.298	.132	.356
C4	.095	.136	.215	.334
P4	.049	.098	.116	.276
O2	.032	.064	.049	.184
F8	.284	.281	.540	.601
T4	.061	.071	.388	.433
T6	.040	.068	.192	.293
RM	−.001	.004	.261	.279

Comparisons Among Methods

In the previous sections several techniques for dealing with the ocular artifact have been described. Tables 2 and 3 report a comparison of the main features of time domain methods and frequency domain methods, respectively. In the evaluation of correction techniques, two questions arise: (1) Can these techniques be relied on to eliminate or substantially reduce the ocular artifact? and (2) Which of these techniques works best? Each of the various papers reporting on the various techniques reviewed here shows clear improvements in the quality of EEG and ERP data after correction of the ocular artifact. However, it is difficult to establish a general criterion for determining which technique works best.

Early attempts to compare several methods for correcting ocular artifacts were carried out by Berg (1986) and by O'Toole and Iacono (1987). A more thorough comparison was carried out in 1987 and presented at a meeting that was organized in Tilburg. The meeting included the Tübingen group (Lutzenberger and Elbert), the Tilburg group (van der Berg-Lenssen and Brunia), the Sheffield group (Jervis, Ifeachor, and Coelho), the Illinois group (Gratton and Coles), the Heidelberg group (Möcks, Gasser, and Sroka), and the Amsterdam group (van Driel, Woestenburg, and van Blokland-Vogelesang). Each of the groups was given the same data set (obtained in a contingent negative variation experiment) and was assigned the task of applying the EOG correction technique that they had proposed to filter out the ocular artifact in order to compute average ERPs. The data set was relatively exceptional with respect to most data sets used in ERP research because of the very extended recording epoch used (12 sec). The average ERPs and the scaling factors used to correct the EOG artifact obtained by each group were then compared. The results of this comparison process, published in 1989 in the *Journal of Psychophysiology* (Brunia et al., 1989), indicated that the outcome ERP waveforms were, in general, very similar to each other, although some small differences emerged for very slow frequencies.

Although the comparison effort was laudable, the outcome is somewhat ambiguous. A major limitation of the comparative study is that there is no independent criterion to determine which technique worked the best. Once techniques were found to produce slightly different results, it was unclear which of them produced the optimal correction. A criterion based on the reduction of variance in the output (i.e., smaller residual variance, such as that used by Berg [1986] or O'Toole & Iacono [1987]) does not have a strong inherent logic. Recently, Kenemans, Molenaar, Verbaten, and Slangen (1991), as well as van den Berg-Lenssen, van Gisbergen, and Jervis (1994) used simulations to evaluate the validity of different methods in the time and frequency domain, observing little difference between the correction methods. A limitation of the simulated work is that the conclusions depend on the validity of the assumptions made to produce the simulated data.

Table 2
Comparison of Some of the Time Domain Techniques for Correcting the Ocular Artifact

Technique	Time of Use	Requires Calibration Epochs	Method of Estimation of Scaling Factors	Number of EOG Channels	Distinction Between Blinks and Eye Movements	Consideration of Event-Related Activity
McCallum & Walter (1968)	On line	Yes	Compensation	1	No	—
Girton & Kamiya (1973)	Off line	Yes	Division	1	No	—
Quilter et al. (1977)	Off line	No	Regression	1	No	No
Barlow & Remond (1981)	On line	Yes	Compensation	2	No	—
Verleger et al. (1982)	Off line	No	Regression/Average	1	No	No
Fortgens & de Bruin (1983)	On line	Yes	Compensation	4	Yes	—
Gratton et al. (1983)	Off line	No	Regression	1	Yes	Yes
Ifeachor et al. (1986)	On line	Yes	Regression	3	No	—
Elbert et al. (1985)	Off line	No	Regression	3	No	Yes
Semlitsch et al. (1986)	Off line	No	Regression	1	No	Yes (blinks)
Gratton & Coles (1989)	Off line	No	Regression	2	Yes	Yes
Jervis et al. (1989)	Off line	No	Regression	3	No	No
van den Berg-Lenssen et al. (1989)	Off line	Yes	Autoregression	3	No	—
Berg & Scherg (1994)	Off line	Yes	Dipole modeling	3	Yes	—

Table 3

Comparison of Some of the Frequency Domain Techniques for Correcting the Ocular Artifact

Technique	Time of Use	Requires Calibration Epochs	Method of Estimation of Scaling Factors	Number of EOG Channels	Distinction Between Blinks and Eye Movements	Consideration of Event-Related Activity
Whitton et al. (1978)	Off line	No	Regression	1	Yes	No
Woestenburg et al. (1983)	Off line	No	Regression	1	Yes	No
Gasser et al. (1986)	Off line	No	Regression	3	Yes	Yes
van Driel et al. (1989)	Off line	No	Regression	3	Yes	No

Similarly, comparisons based on dipole analysis (Berg & Scherg, 1994) are also dependent on the validity of the models used. Furthermore, it is often difficult to evaluate whether the differences observed between techniques would lead investigators to different conclusions about the data. Clearly, if the conclusions were the same regardless of the technique used for correction, the differences would be, for all practical purposes, trivial.

Conclusions and Guidelines

In summary, the EOG contamination of EEG and ERP data is a serious, very common problem. Data in which this problem is not dealt with in a satisfactory manner should not be published (Donchin et al., 1977). In general, the presence of eye movement and blink artifacts should be monitored with dedicated EOG channels (the use of only EEG channels makes the interpretation of large potentials ambiguous). Although a vertical EOG channel may be sufficient for monitoring for the presence of blinks and vertical eye movements, it is insufficient for determining the existence of lateral eye movements. This is a significant problem at lateral electrode locations and/or when an asymmetric reference is used. At least two EOG channels (vertical and horizontal) are required, and the utility of a third channel is still under debate (see commentaries of the Brunia et al., 1989, paper). A third channel could in principle be useful to improve correction of EOG artifacts, but it is not clear that it results in significant changes in the corrected waveforms. It appears that the use of two dedicated EOG channels is sufficient for most purposes, and that a third dedicated channel may be needed only when large changes in eye convergence are expected.

At least two general strategies are available to the experimenter. One is to reject trials in which eye movements or blinks are deemed to occur. This is computationally very simple, but it will lead to loss of data, and, in some cases, to biasing of the data sample. The other is to apply one (or more) of the many procedures that have been proposed to correct for the EOG contribution to the EEG and ERP.

Correction methods involve some assumptions about which model of the EOG artifact is more appropriate. Both on-line and off-line methods of correction are available. By and large, off-line methods are more flexible and reliable. Given the present capabilities of personal computers, the application of off-line correction methods may add only a very short amount of time to the computation of average ERP waveforms. EOG correction can be carried out either in the time or the frequency domain. Time domain methods are computationally simpler and less sensitive to high-frequency EEG contamination of the EOG trace. Frequency domain methods, on the other hand, are less sensitive to inaccuracies due to slow drifts in potential. For both types of methods, there exist appropriate techniques to minimize the probability of inaccurate compensation of the ocular artifact. When such techniques are correctly applied, the outcome of the various methods tend to converge, although subtle differences may remain.

A practical difference between correction methods is the requirement (or lack thereof) of calibration trials. The advantage of calibration trials is that correction can be carried out on line. This advantage appears less important today than it did a few years ago, since off-line computation of corrected ERP waveforms may now be performed in just a few minutes even with small personal computers. The use of calibration trials has also been advocated for reducing the possibility of correcting the "true" ERP in the case in which both EOG and ERP effects are time locked to the stimulus (or, in the case of frequency domain methods, share a similar power spectrum). As seen above, this can be addressed by using "non–time-locked" EEG activity for the computation of the propagation factors (see Gratton et al., 1983). In the case of frequency domain methods, this requires computing the EEG and EOG power spectrum after subtraction of the time-locked activity. The use of calibration trials is itself not free of problems. First, the recording of calibration trials requires additional time. Second, calibration trials may be accompanied by ERP activity of their own—albeit probably of a different nature than that observed during regular ERP studies. This may alter the propagation factors computed during the calibration period, introducing some different form of spurious correlation between EOG and EEG. Third, eye movements during calibration trials may not be representative of the type of movements that occur during regular ERP studies, since voluntary eye movements may involve eyelids to a different extent than do involuntary (or reflexive) movements. This may be particularly problematic in the case of eye blinks. Overall, the use of calibration trials does not appear necessary, provided that procedures are taken to ensure that the propagation factors are not influenced by spurious correlations between the timing (or the frequency spectra) of EOG and ERP activity.

Most EOG correction procedures improve the quality of the data significantly. However, there may be occasions in which the procedures fail. It is therefore critical to determine whether the propagation factors are computed appropriately. One simple way to identify major failures in the estimation of the propagation factors is to inspect or plot the propagation factors as a function of the location of the recording electrodes over the head. It can be expected that the propagation factors should decrease from the front to the back of the head (i.e., as a function of distance from the eye). In addition, the propagation factors for the horizontal EOG should have opposite signs on the two hemispheres and should be smaller at midline than at lateral electrodes. Propagation factors should be smaller than 1, and typical values for Fz are around .25–.35; for Cz, around .10–.15; and for Pz, around .05–.10 (using an average mastoid or ear reference), with slightly smaller values for blinks than for eye movements. Large departures from this pattern indicate the presence of errors in the computation of the propagation of the EOG over the head.

There are two main reasons for errors in the computation of the propagation factors. First, the quality of the data is poor, either because of large electric drifts (more likely to generate problems for time domain than for frequency domain methods) or because of other types of noise (whose influence on the results will vary from case to case). This may be solved partly by the elimination of trials with large artifacts of nonocular origin before the application of the correction procedure (the nonocular origin of an artifact can be ascertained by plotting simultaneously EEG and EOG traces; computerized algorithms for artifact detection can also be used). Second, there may be too few ocular artifacts to afford a reliable computation of the propagation factors. This is usually not a serious problem, since most correction procedures will produce little change in the data in this case (as should be the case).

Small errors in the computation of propagation factors are very hard to detect. In most cases they are not serious, since they will lead to small errors in the estimation of the "true" ERP. However, they may be problematic when the experimenter is interested in very tiny effects (fractions of a microvolt). When the interest is in very small ERP activity, it may be useful to generate conditions in the experiment that minimize the possibility that small under- (or over-) corrections of the ocular artifact may contribute significantly to the experimental variance. This can be achieved by creating experimental conditions in which eye movements are expected to be as similar as possible. Inspection (and quantification) of EOG effects may be useful for verifying whether this strategy actually has worked.

Since several EOG correction methods exist, one may ask which is the best method for any particular condition. It is very difficult to give a definite answer to this question, since the "true" ERP is not known. However, the results of the Tilburg meeting (Brunia et al., 1989) suggest that this answer may not be necessary for most practical purposes. In fact, when appropriate methodologies are used in order to take care of problems inherent in the various approaches (such as the influence of slow shifts, particularly critical for time domain methods; the possibility that "true ERP" activity is temporally correlated with the EOG artifact, a problem for both time domain and frequency domain methods; the presence of EEG in the EOG trace, most problematic for frequency domain methods; etc.), the results tend to converge. This convergence indicates that there exists no special advantage in correcting the ocular artifact in the frequency domain with respect to the time domain (and vice versa), suggesting that the propagation factors may be generally constant across frequencies (or, more precisely, that departures from constancy are not important). Practical factors, such as computational load, availability of the software, or convenience of application, may then become important in the selection of a particular EOG correction procedure. In any case, it is essential that eye movement artifacts are eliminated from the data before any conclusion about brain activity is drawn from ERP studies.

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