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REVIEW ARTICLE

Removal of ocular artifact from the EEG: a review

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Summary – Eye movements cause changes to the electric fields around the eyes, and consequently over the scalp. As a result, EEG recordings are often significantly distorted, and their interpretation problematic. A number of methods have been proposed to overcome this problem, ranging from the rejection of data corresponding temporally to large eye movements, to the removal of the estimated effect of ocular activity from the EEG (EOG correction). This paper reviews a number of such methods of dealing with ocular artifact in the EEG, focusing on the relative merits of a variety of EOG correction procedures. Issues discussed include the distinction between frequency and time domain approaches, the number of EOG channels required for adequate correction, estimating correction coefficients from raw versus averaged data, differential correction of different types of eye movement, the most suitable statistical procedure for estimating correction coefficients, the use of calibration trials for the estimation of correction coefficients, and the distinction between 'coefficient estimation' and 'correction phase' error. A suggested EOG correction algorithm is also described. © 2000 Éditions scientifiques et médicales Elsevier SAS

AAA / artifact / correction / EEG / EOG / ocular / RAAA

Résumé – Retrait de l'artefact oculaire de l'EEG : synthèse. Les mouvements oculaires produisent des changements de champ électrique autour des yeux, et par conséquent sur le scalp (électrooculogramme, EOG) ; cela entraîne des distorsions, souvent significatives, du signal EEG, rendant son interprétation problématique. Plusieurs méthodes ont été proposées pour pallier ce problème ; elles vont du simple rejet des données EEG contemporaines à des mouvements oculaires de grande amplitude, à l'élimination plus sélective de l'effet spécifique de l'activité oculaire sur le signal EEG (correction de l'EOG). Cet article passe en revue la plupart de ces méthodes de correction, en soulignant leurs avantages et inconvénients relatifs. Parmi les items discutés figurent la distinction entre les approches fréquentielles et temporelles, le nombre de canaux nécessaires pour une correction adéquate, les procédures statistiques les plus appropriées pour l'estimation des coefficients de correction, et la distinction entre les erreurs dues à l'estimation des coefficients et celles qui sont liées à la correction de phase. Enfin, nous décrivons également un algorithme de correction qui tâche de minimiser les différents problèmes soulevés. © 2000 Éditions scientifiques et médicales Elsevier SAS

AAA / artefact / correction / EEG / EOG / oculaire / RAAA

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GENERAL INTRODUCTION

Eye-movements are a major source of contamination of the electroencephalogram (EEG). This is because eye-movements cause a change in the electric fields that surround the eyes, and these distort the electric fields over the scalp. Since the EEG is a record of the electrical activity over the scalp, the EEG is distorted. For example, in *figure 1* the effect of a large vertical eye-movement on the EEG can be seen. In measuring the EEG, we are typically interested in the underlying neural potentials (bold line), but our recording is of the combination of neural and eye-movement potentials (thin line).

Eye-movements are not only of theoretical concern to researchers, but affect the results that they obtain as well. For instance, Low et al. noted in their contingent negative variation (CNV) study that the scalp event-related potential (ERP) corresponded to a consistent eye-movement, making interpretation difficult [28]. This observation was confirmed by Hillyard and Galambos [23], who established that in most of their subjects, a significant portion of the CNV was due to eye-movement, and not solely neural potentials as had been previously thought. There are similar difficulties for quantitative EEG. For example, Gasser and co-workers found that eye-movements increased the power of low frequency bands in schizophrenic patients, and also that they decreased the chance of finding significant differences between the schizophrenic and control groups [18].

Consequently, researchers must take into account the effect that ocular activity has on the EEG. This might mean anything from rejecting all or some of a subject's data, reinterpreting the data, or applying one of the many correction procedures available. That it cannot be taken lightly is stressed in Donchin's et al. guidelines for the publication of ERP investigations [13], where it is stated that "the measures taken to deal with this problem [ocular artifacts] should be considered in any published report."

How is the eye-movement voltage generated?

A number of studies have tried to ascertain where the eye-movement voltages are generated. Some researchers simplify matters by assuming that there is either only one generator, or that our treatment of the EEG data will be reasonable if we assume this, whilst others believe the possible complexity of the voltage generator

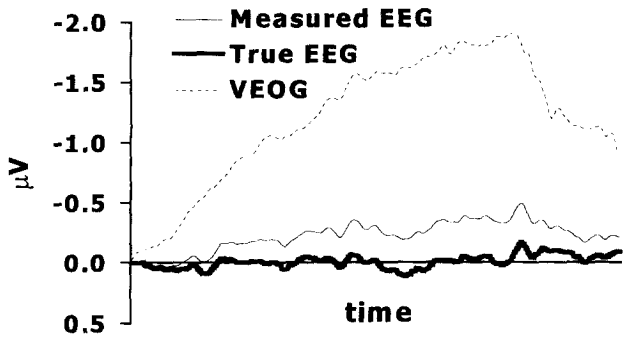

Figure 1. The effect of ocular potentials on the EEG is demonstrated. A neural potential at Fz that we may be interested in (bold line) is made more negative (thin line) by a large eye-movement voltage (dotted line). If we do not account for the negative shift caused by the eye-movement, we will conclude that the neural potential is more negative than it is.

sites to be an important factor in the treatment of ocular artifact. Three mechanisms have been proposed.

Cornea-retinal dipole movement

The eye forms an electric dipole because the cornea is positively and the retina negatively charged. When this dipole moves (e.g., the subject looks up), the electric field around the eyes changes, which in turn affects the electric fields over the scalp generated by neural potentials. This tends to be the standard view [6, 22].

Retinal dipole movement

This is similar to the above view, differing only in that the dipole is attributed to the potential difference across the retina, with the cornea having little effect [3, 5]. The distinction is important because this view places the source of eye-movements more posterior than the source of blinks, which could complicate efforts to account for them in the EEG.

Eyelid movement

It has been established that the voltage around the eyes is affected by the movement of the eyelids over the eyeball, even when there is no rotation of the eyeball [30]. It is thought that the eyelid acts as a sliding potential source, and that this type of ocular activity (blinking) affects the EEG differently than the eye-movements described above [20]. It has been argued that the source of such blinking artifacts is anterior to the source of other types of eye-movement artifact [5].

Typical patterning of the eye-movement voltages across the scalp

The 'propagation' of eye-movement voltages to scalp sites is dependent on a number of factors (such as the filter properties of the subject's skull, scalp and neuronal tissues), but as an approximation, the voltage is inversely related to the square of the distance from the eyes [38]. In general, about 0.20 of the vertical eye-movement voltage reaches Fz, with the amount decreasing posteriorly to about 0.05 at occipital sites, and with little effect of laterality.

Horizontal eye-movement voltages decrease in a similar fashion posteriorly, but also vary laterally. When measured as a difference in voltage between the outer canthi of the left and right eyes (see "How do we measure the eye-movements?"), this difference in voltage propagation is positive on the left, and becomes more negative as we move to the right-hand side of the scalp. There often appears to be no effect of horizontal eye-movement on central sites, suggesting that these voltages cancel each other out and do not affect the EEG at midline sites. Contrary results have been reported, but these may be due to errors in propagation estimation. This is suggested because different methods applied to the same data set have produced different estimates of midline horizontal eye-movement contamination (compare the different researchers' estimates at the Tilburg symposium [6]).

How do we measure the eye-movements?

The electrooculogram (EOG), from a series of electrodes recording voltage changes close to the eyes, is the most widely used measurement tool for dealing with eye-movement artifact in the EEG. Other methods have been employed (such as retinal reflection and videography), but these are only appropriate for the rejection of large eye-movements and, as argued below, this rejection method is an inadequate means of dealing with ocular artifact.

It is thought that the various components of eye-movement artifact can be recorded with three orthogonal EOG derivations, vertical, horizontal and radial [14]. For vertical eye-movements we use the vertical EOG (VEOG), the difference between voltages recorded above and below the eye or eyes (e.g., E1 – E3 in *figure 2*). The advantage of this subtraction process is that it reduces the neural potentials in the EOG, as an amount of the neural potential reaching E1 will also reach E3, and thus will be subtracted out of the VEOG.

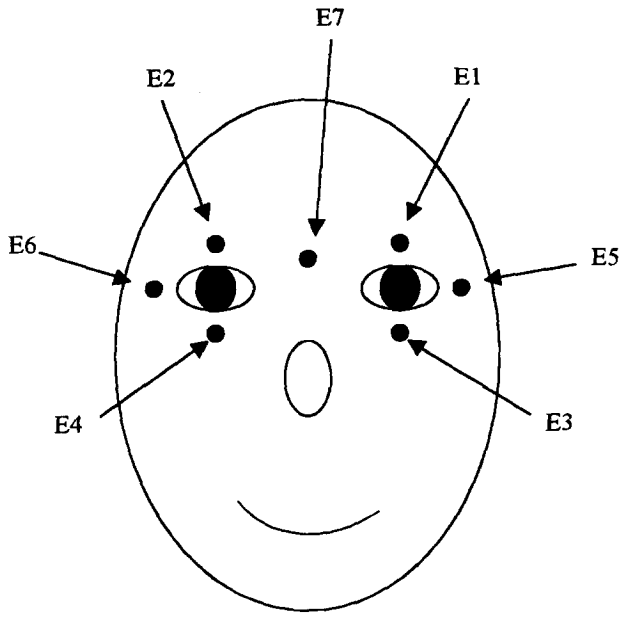

Figure 2. The electrode placement scheme used at the Tilburg symposium [6].

Horizontal eye-movements are measured with the horizontal EOG (HEOG), typically the difference between the voltages at the left and right outer canthi of the eyes (e.g., E5 – E6 in *figure 2*). The radial component is measured by subtracting the average voltage at the eyes from the reference electrodes (e.g., [(E1 + E3)/2]– reference used for EEG; *figure 2*). Recent results from our laboratory suggest that VEOG, HEOG and REOG are all necessary for accurate correction [10]. However, many combinations of these derivations are currently used, with no consensus as to the optimum configuration.

Methods for accounting for ocular artifacts

Recording with eyes closed

Although limiting task type, this method may be useful in reducing fast eye movement such as blinking and visual fatigue. However, caution should be applied when utilizing this method as slow-frequency eye movement may increase due to lack of visual reference, and changes in EEG spectra may occur (e.g., it increases alpha activity because of reduced visual input). Further,

it has been found inferior to EOG correction procedures [34], suggesting that correction methods may be more appropriate.

Experimental control

Having subjects fixate on a point generally reduces slow eye-movement and blinking [23]. However, this method may complicate interpretation as it imposes secondary demands on the subject that have been shown to affect the N1 and P3 ERP components [45], as well as the CNV complex [48]. Significant eye-movement due to the subjects' inability or reluctance to follow the instructions may also be a problem, especially with certain populations (e.g., children with attention deficit/hyperactivity disorder, schizophrenic patients). If not too restrictive, designing experiments that do not require eye-movements or result in too much visual fatigue would prove the most successful form of experimental control.

EOG rejection

Rejection procedures omit trials with large eye-movements from analysis, and are typically used in conjunction with experimental control. Artifact trials are defined as trials with VEOG greater than a preset criterion and are removed from further analysis. A criterion of 50 μV may be set, for example, and any trial with a VEOG deflection greater than 50 μV (relative to baseline) is eliminated.

The problems with this approach are numerous. Firstly, it does not reject trials with small VEOG, and these can affect results [39]. This cannot be avoided, because if we set the rejection criterion low enough to remove most of the eye-movement artifact from the EEG, we will have very few usable trials, and further, some trials would probably be rejected because of prefrontal EEG picked up in VEOG. Secondly, this method would omit possibly useful information. For example, because of the close link between eye-movements and cognition [1], we may be rejecting data relevant to our study. This is particularly important when we compare populations who may exhibit differing types or levels of eye-movement, as the differential removal of data may create a bias. Correspondingly, should an ERP signature of a subject's condition be temporally linked to large eye-movements, we could not identify it with this technique. For example, the early ERP components of the startle response have been very difficult to analyze because, by definition, they are temporally related to blinks [36].

Further, empirical studies assessing the merit of this method have found it inadequate and inferior when compared to the correction methods that follow [34, 46]. We would thus not recommend rejection as a suitable means of dealing with ocular artifact.

EOG correction

Instead of removing the EEG data affected by eye-movement from the analysis, correction procedures attempt to remove the effect of the eye-movement from the EEG. For example, they may estimate that 0.20 of the VEOG channel is contaminating an electrode, and so at every time point, they subtract 0.20 of VEOG from the EEG.

Early analogue techniques

The main problem with the early analogue correction procedures is that they are not sensitive enough to obtain accurate estimates of the ocular effect. For example, in Girton and Kamiya's online correction, calculation of a 'correction coefficient' involved adjusting an attenuator while the subject made extreme eye-movements [19]. The attenuator fed back from the EOG to the EEG channel, where the attenuated voltage was subtracted from the EEG voltage. There were only ten possible attenuation factors, with the optimal setting coming from the one that visually yielded "minimal eye-movement artifacts in the corrected EEG trace." It is not surprising that subsequent frequency analysis found that although visually it seemed to correct well, EOG did remain in the corrected EEG [49], and that such analogue methods have been found inferior to the mathematically based ones that follow [25]. Thus we shall not deal fully with such analogue procedures.

Advanced regression techniques

A major improvement on the analogue techniques was the use of the 'least squares' regression function introduced by Quilter and co-workers [37]. The regression function calculates *B*, the proportion of one variable that is explained by another, and in terms of EOG correction, an estimate of the amount of EOG that is present in a particular EEG channel. Formally this is given in Eqn. 1, where X_i represents the EOG and Y_i the EEG voltage at time *i*. A separate *B* is calculated for each subject and electrode site. The equivalent formula of Eqn. 2 is perhaps more intuitive. Here we have r_{xy},

the correlation between the EOG and EEG channels, and it has been scaled by the standard deviations of the two channels to yield the same result.

$$B = \Sigma(X_i - \overline{X}_i)(Y_i - \overline{Y}_i)/\Sigma(X_i - \overline{X}_i)^2 \quad (1)$$

$$B = r_{xy} \cdot sd_y/sd_x \quad (2)$$

This is referred to as the time domain approach (TDA) because it compares voltages from EOG and EEG channels at each time point, irrespective of frequency. Correction then takes place as per Eqn. 3, where at a particular scalp site, *est*TEEG is the estimated true neural potential and $MEEG_i$ the measured EEG at time *i*, *B* is the propagation coefficient described in Eqn.s 1 and 2, and C is the y-intercept of the regression equation. The subtraction of C is to remove the EOG baseline effect from the EEG, and its calculation is described in Eqn. 4, where X and Y are as defined in Eqn. 1.

$$estTEEG_i = MEEG_i - (B \,.\, EOG_i) - C \quad (3)$$

$$C = \overline{X}_i - (\overline{Y}_i \,.\, B) \quad (4)$$

The obvious extension of this procedure is to use two EOG channels, generally VEOG and HEOG, but it can be extended to include any number of channels. The principle is the same, but the formulae are a little more complex. *B* is calculated for each EOG channel using Eqn. 5, where $B_{yx\,.\,z}$ is the propagation value from EOG channel X to EEG channel Y, after taking into account the influence of EOG channel Z, sd is standard deviation and *r* the Pearson's product-moment coefficient. *B* is calculated separately for each EOG channel. We then correct with Eqn. 6, differing only from Eqn. 3 in so far as it subtracts a portion of *each* EOG channel.

$$B_{yx\,.\,z} = ([r_{yx} - r_{yz}\,.\,r_{zx}]/1 - r_{xz}^2) \,.\, sd_y/sd_x \quad (5)$$

$$estTEEG_i = MEEG_i - (B_{yx\,.\,z} * EOG_{xi}) - (B_{yz\,.\,x} * EOG_{zi}) - C \quad (6)$$

Validation of correction procedures

One of the major problems in EOG correction research is that no obvious method of validation has been available. This is because we do not have an accurate means of measuring uncontaminated neural potentials, and so we do not have a criterion against which to measure the success of the correction methods. Consequently, researchers' validity criteria tend to be less than ideal. For instance, based on the assumption that there is no correlation between EOG and uncontaminated EEG, Verleger et al. proposed a low EOG/corrected EEG correlation as a criterion for good correction [46]. Although a useful guide, this cannot be a conclusive test due to the genuine correlation between EOG and neural potentials [23], the reason for originally devising correction methods.

Another validation criterion was that uncontaminated ERPs should be similar to corrected ERPs [20]. Because uncontaminated trials cannot be obtained, ERPs composed of trials that did not contain EOG above a certain criterion were used. This means that the test of validity is whether corrected ERPs resemble ERPs contaminated by small eye-movements, allowing a reasonable but again not refined measure of validation.

Verleger et al. also proposed that corrected waveforms should have face validity: they should look reasonable [46]. Although this does not offer an explicit test of a method's effectiveness, we believe that it is the most useful form of validation because it utilizes the experience of the experimenter. For this to be useful, corrected data must be in an easily accessible form, and in our view the averaged corrected neural potentials resulting from eye movements are in such a form.

That is, as opposed to assessing the correction of an ERP waveform, for example, where the effect of ocular potential is partially removed through averaging and is summed with the ERP, the eye-movement average maximizes the contribution of the ocular potential, and has far smaller neural potentials accompanying it. Because of this, this method is conducive to visual inspection, and so we do not have to rely on the statistical tests of adequacy that are generally used to evaluate ERP and EEG corrected data [16, 20]. For example, *figure 3* shows a corrected eye-blink average (using the RAAA technique described). The result of the correction is a waveform that should only contain neural potentials related to the blink, and so the validity of the correction can be ascertained by judging the reasonableness of the resultant ERP components and their scalp distributions.

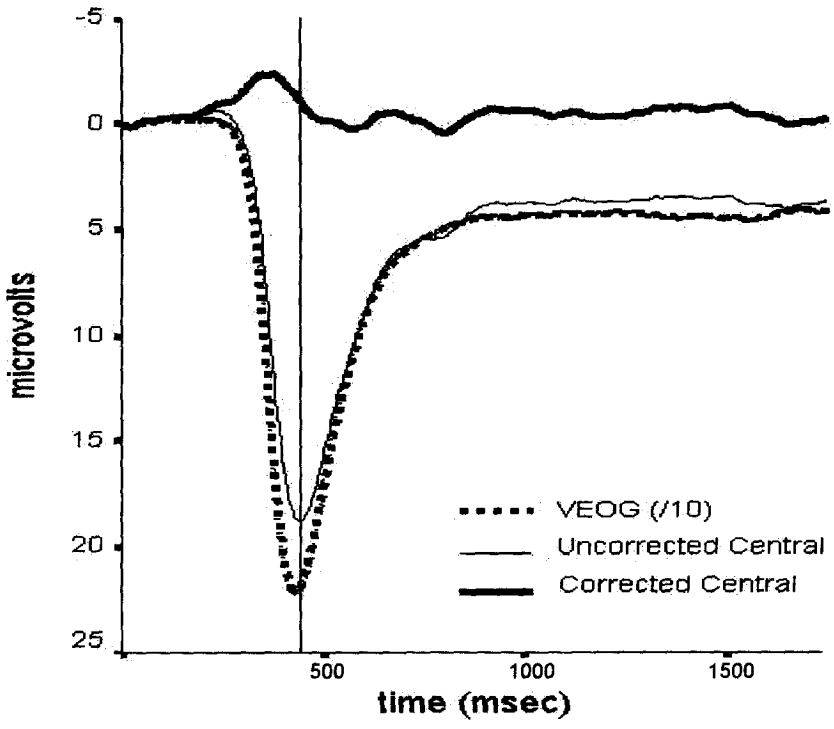

Figure 3. The average corrected waveform for the central sites of 15 subjects is shown, along with the corresponding raw waveform and the vertical eye movement channel (scaled to allow comparison).

ISSUES RELATING TO EOG CORRECTION

There are many different types of EOG correction procedure. For example, some separate blinks and non-blinks and correct separately, while others separate the different frequencies of voltage associated with eye movements and correct separately. Some use calibration data, others use the experiment data to estimate correction coefficients, and there are a number of ways of accounting for the *B* distortion caused by interference in the EEG and EOG channels.

Differences in EOG correction methodology may result in significant variation in corrected data. For example, if two different eye-movement types propagate similarly and we apply a different *B* to each type, then one of the *Bs* will be inaccurate and the 'correction' procedure will introduce ocular artifact into the EEG. If they propagate differently and we correct with only one *B*, that will be inappropriate for one eye-movement type, and again the 'correction' will introduce ocular artifact. It is thus important to consider a number of such issues below.

Do we need to calculate *B* separately for blinks and other types of eye-movement voltages?

A number of studies have reported that blink and saccade voltages propagate differently [7, 20, 24, 27, 35], and corresponding to this it is generally claimed that these artifact types should be corrected separately [4, 22]. However, recent research has shown that this distinction is at least in part the result of the inability of traditional methods to deal effectively with interference in the EOG and EEG channels, such as D.C. shift and the forward propagation of neural potentials to the EOG channels [8].

Consequently, it has been shown that when the sources of interference are removed from the EOG and EEG, differences between blink and non-blink *Bs* are also removed [9]. For example, reducing the degree of

influence that D.C. shifts had on *B* decreased the difference between blink and non-blink *Bs*, and removing both D.C. shift and the neural potentials that had propagated forward to the EOG removed this discrepancy completely. This study used data from five subjects using Fz and VEOG only, but a recent extension of this study has shown that when HEOG and REOG are accounted for adequately, there is no difference between blink and non-blink correction at any scalp site [10]. Consistent with these findings, some researchers have failed to find differences between blink and non-blink *Bs* [6, 19].

Therefore, it is recommended that blinks and saccades be corrected together, so long as a suitable means of removing interference is used (see 'Recommended correction procedure').

Do we need to calculate *B* separately for different frequencies of eye-movement?

It has been argued that due to the different attenuation characteristics of the various media between the eyes and EEG sites, eye-movement voltages propagate differently for the different frequencies involved with eye-movement [49]. Correspondingly, some researchers have opted for a frequency domain approach (FDA) for correction [16, 18, 50], differing from the time domain approach in that separate *Bs* are calculated for different frequencies of EOG. The term 'transfer function' is used to denote FDA correction coefficients, but to keep matters simple we shall refer to them as *Bs*, as in the time domain. The mathematics for this approach is not simple and will not be dealt with here; formulae are given elsewhere [50]. In support of this approach, exponents of the FDA have reported different *Bs* for different frequency ranges above 5 Hz [16, 17, 32, 50].

However, the advantage of FDA is yet to be established, with a number of studies finding that it produces equivalent results to that of the time domain approach [6, 26, 42]. Further, within the frequency range relevant to eye-movement, attenuation *is* relatively constant [33], suggesting that the *B* variation among the different frequency ranges above 5 Hz may be artifactual, due to the differing levels of EOG power that *Bs* are calculated from [8].

Therefore, although it has not been shown that the frequency domain approach is inaccurate, its utility has not been demonstrated either, and so, as there are possible problems with the approach (described above), its use is not recommended.

How best to account for interference in the EOG and EEG channels

It was argued earlier that interference occurring in the EOG and/or EEG channels will distort *B* unless the EOG is sufficiently large, relative to the EEG [9]. That research suggested that EOG will not be sufficiently large except when correcting eye-movements at frontal sites using blinks or equivalently large EOG to calculate *Bs*. Therefore, we believe that for most cases, we do need to account for interference in the channels.

The types of interference that are generally encountered in EOG correction are those of forward propagation (the influence of neural activity on EOG recordings) and D.C. shift, both of which cause an overcorrection of the EEG. Background EEG can also be viewed as interference, because when EOG is small, eye-movement voltage can be 'lost' in the background voltages, thus causing *B* to be underestimated. We shall consider a number of approaches designed to minimize these influences.

Calibration trials

Calibration trials are pre-experiment sessions where the subject makes large eye-movements in order to obtain a *B* estimate (see 'Can we use calibration trials to calculate correction coefficients?'). These are thought to reduce the effect of forward propagation because they do not have the experiment-related neural potentials propagating forward [43]. However, forward propagation will still inflate *B* during calibration trials because it makes no difference whether the forward propagation is related to the experiment or not; any forward propagation will inflate *B* estimates. Thus this method will not solve the problem caused by forward propagation.

Modeling of the EEG

Gratton et al. designed a method that tried to remove forward propagation in ERP studies by calculating ERPs in the usual way for all channels, including EOG, subtracting the ERP from the raw epochs of that channel, and calculating *B* from the remaining 'raw ERP' data [20]. This method has two major problems. Firstly, it minimizes EOG power because the EOG tends to be time-locked to the evoking stimuli [23], and so when the ERP is subtracted from the raw data, a portion of EOG is removed too. Such power reduction has been shown to adversely affect *B* estimates [8, 9]. Secondly, the reduction in artifact that it does achieve is limited to event-related artifact, which is only a small portion of the artifact that distorts *B* estimation.

Lutzenberger and Elbert proposed a variation of this procedure [29], as did Jervis et al., who tried to remove the ERPs from the *B* calculation by modeling them and including them in the regression equation [24]. These both suffer from the same problem of EOG power reduction as Gratton's et al. method, and will not be discussed further.

Gasser and colleagues attempted to overcome the effect of neural potential contamination of the EOG by estimating the proportion of EEG that had propagated to the EOG channels during epochs of low EOG activity [16]. This amount was then subtracted from *B*, the EOG-to-EEG propagation estimate. This method was performed in the frequency domain, and the problem with it is that it assumes that there is negligible propagation from EOG to EEG during these epochs. Gasser et al. believed this to be a reasonable assumption. However, during low power EOG epochs, the EEG channel is only of a similar magnitude to the EOG, which is not nearly large enough to obtain an accurate propagation estimate [8]. Consequently, there will be inaccuracies in the EEG-to-EOG propagation estimate, the adjustment to *B*, and ultimately the correction itself.

A priori cut-offs

The frequency domain approach offers a solution to the problem of artificial *B* inflation, as it can selectively remove only the frequencies thought to be ocular-related. For instance, a cut-off criterion might be employed, above which it is thought that a propagation coefficient must be artifactual, and only those frequencies with *Bs* below this value are removed [44]. However, as we are not aware of any theoretical or empirical rationale for employing a particular cut-off, we would not advise using this method. For instance, the cut-off employed by van Driel and co-workers [44] was 0.7, which is over twice as large as time domain and other frequency domain *Bs* [16, 22]. It also appears counter-intuitive to correct when $B = 0.65$, and yet not correct at all when $B = 0.70$.

Source localization

Multiple-source eye correction is a variant of dipole modeling and offers another way of removing the effect of forward propagation from *B* [5, 27]. The primary difference between this and other methods is that it estimates the *source* of the ocular artifact, which by definition is independent of artifact, and corrects with this. The method is based on principle components analysis, and variants based on independent components analysis have also been proposed [47]. The accuracy of these methods depends on the accuracy of the head model used, and thus if an MRI scan (for instance) can be obtained from the subject, this offers a very strong method of ocular artifact removal. However, as general head models will not be accurate near the eyes [5], they will not give an accurate correction. Thus its utility is limited at present.

Increasing EOG power

Some researchers attempt to overcome the problem of interference by using epochs with large EOG power to calculate *B* (either using calibration or experimental data), as this will minimize the relative size of the interference, thus making *B* estimation more accurate [46, 50]. The rationale behind this method is valid, as *Bs* should only be calculated from high-power EOG (relative to EEG), but it does not go far enough toward solving the problem. That is, it has been shown that even within high-power epochs, the size of the EOG is *not large enough* to overcome the problem at posterior sites [9], and thus a way of increasing the EOG/EEG ratio beyond what can obtained from standard recordings must be employed.

Separation of ocular from other EOG voltages

Another method of removing interference in the *B* estimation process is to only calculate *Bs* from the voltages resulting from eye movement. For instance, Attias and colleagues use EOG to calculate *Bs* only if the voltage below the eye is the opposite phase of the voltage at Fz [2]. This may be thought to remove the forward propagation of neural potentials to the EOG, for instance, because this would be of similar phase below the eye and at Fz. However, this procedure will only be useful for detecting large eye-movements, because this 'opposing-phase pattern' will be obscured by neural activity during small eye-movements. Further, even these large eye movements will be susceptible to *B* inflation, as is the case for other large eye-movements (see 'Increasing EOG power').

Aligned-artifact averaging

The advantage of large EOG power discussed in this paper is extended with the aligned-artifact average procedure (AAA) [9]. It is based on the logic behind the ERP, averaging a number of eye-movements to remove artifact sources not time-locked to the eye-movements. As the number in the average increases, EOG magnitude increases relative to the EEG, as does the likelihood of obtaining an accurate *B*. In effect, this proce-

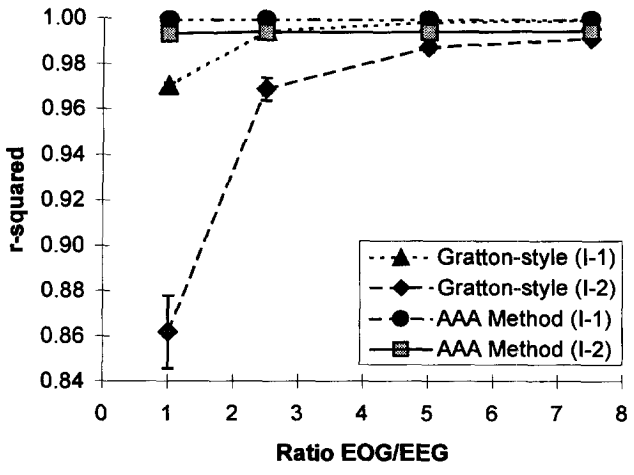

Figure 4. True-to-corrected concordance values are shown for simulated data, using the AAA and a Gratton-style procedure (i.e., not employing the correction for forward propagation [9]). Two levels of interference are used, one employing forward propagation only (I-1), and the other forward propagation plus a D.C. shift (I-2). X-axis represents the ratio of EOG-to-EEG magnitude. It can be seen that the AAA is not affected by either interference condition, whereas the Gratton-style is. The Gratton-style can be seen to be particularly susceptible to the effect of the D.C. shift.

dure is an extension of the method of Semlitsch et al. [40], who averaged blinks to calculate a blink *B*. The difference with the AAA is that whereas they thought the correction of non-blinks too problematic, the AAA is appropriate for the correction of *all* ocular artifact.

A calibration trial is used in this procedure (see 'Can we use calibration trials to calculate correction coefficients?' for a justification of their use), with a series of large eye-movements that are later averaged, and the resultant *Bs* applied to the experiment data collected subsequently. Because the EOG/EEG ratio is greatly increased, it is not only appropriate for frontal site correction, but for all scalp locations.

This method has been tested with subject data, (where *B* variation that occurred using a traditional non-averaging method was removed), as well as with simulation data (where the true to corrected concordance using this method was nearly perfect, and significantly better than the traditional comparison method; see *figure 4*) [9].

It should be noted that forward propagation is of little concern in the AAA. This is because most of it is cancelled out in the averaging process prior to *B* calculation. All that is left is the propagated portion of the neural potential related to the eye-movement-evoking stimuli, and the eye-movement itself. The effect of removing this residual error has been shown to affect the calculation of *B* negligibly [9], and even this small error can be reduced by making the overall neural potentials in the calibration trial orthogonal to the EOG (see 'What condition must be met in a calibration trial').

Do we need to account for phase differences in the EOG?

It has been argued that we must take into account phase differences between the ocular artifact in the EOG and EEG, with various methods devised to do this [16, 26, 50]. However, it has been demonstrated numerous times that there is no measurable delay [16, 26, 43] and so there is no need to account for phase differences.

Can we use calibration trials to calculate correction coefficients?

If propagation fluctuated during recording sessions, then we would need to recalculate *Bs* regularly, and it would follow that calibration trials (sessions prior to the experiment proper designed to facilitate calculation of correction coefficients) should not be employed. Further, if propagation during calibration trials was different from that during the experiment itself, then again they would not be appropriate.

Although such rationales are alluded to, we are not aware of any support for such concerns about the use of calibration trials. People may be concerned by the changes that occur in the cornea-retinal dipole [14], or in the reported differences between cued and spontaneous eye-movements [20], but these will not affect the correction process. For instance, although the cornea-retina potential difference is larger in light than dark conditions, this will only change the magnitude, and not the proportion of ocular artifact that reach a scalp site. Consistent with this, Girton and Kamiya found propagation to be the same after 15 minutes of light or dark adaptation [19], van den Berg-Lennsen et al. [43] found *Bs* constant for at least 30 minutes, and in a recent unpublished study we found *Bs* stable for at least 90 minutes.

Similarly, the distinction between cued and spontaneous eye-movements is only relevant if the eye-movement types propagate at different *rates*. We are unaware of any evidence to suggest that this is the case,

and consistent with this have found that *Bs* calculated from cued and spontaneous blinks using the AAA procedure do not differ [9]. Similarly, O'Toole and Iacono found corrected ERPs to be similar when using calibration and experimental data to calculate *Bs* [34].

What type of regression should we use?

Simple, simultaneous multiple, multiple-stage, or hierarchical regression?

It has been consistently demonstrated that it is best to correct with at least VEOG and HEOG channels [25, 29, 43], and so the question arises as to what type of *multiple* regression to use. Most researchers use simultaneous multiple regression, where all EOG channels are entered at the same time (Eqn. 5) [14, 21]. This eliminates the need to decide on the most important EOG channel, and should minimize the effect of correlations between EOG channels, which have been found to be significant [44].

A multiple-stage regression has also been suggested [44, 50], where the first stage is to calculate *B* for the most important EOG channel (Eqn. 1) and to correct the EEG using this *B* (Eqn. 3). The next stage is to calculate a second *B* using the next most important EOG channel and the partially-corrected EEG, and to correct this partially-corrected EEG using this second *B* (if significant). If there are more EOG channels, the process continues.

However, it has been demonstrated that simultaneous is superior to the multi-stage regression using computer simulations, and thus it is not recommended [10]. It should be noted that such multi-stage regression is different from the procedure of Miller, Gratton and Yee [31], as in their method, EOG channels yet to be used in the correction are de-correlated from EOG channels that have already been used. Thus Miller's et al. method will produce equivalent correction to that of simultaneous multiple regression, and is appropriate for multi-channel correction (although we can see no advantage in employing this over the simpler simultaneous regression).

Should non-significant Bs be used in the correction?

As it might turn out that *Bs* are not significant at some site/channel combinations, when we use simultaneous multiple regression we still have the problem of whether to include non-significant *Bs*. Some opt to omit non-significant *Bs*, because statistically they are due to chance and not eye-movement propagation [50]. Most other researchers include non-significant *Bs*. This is because they may represent real eye-movement propagation that is only non-significant because it is very small. Further, because they are small, it is thought that if they are artifactual they will not affect the data appreciably. We are unaware of any studies assessing the effect of including non-significant *Bs* but, following the rationale of Woestenburg et al., would be hesitant to include non-significant *Bs* [50]. A form of hierarchical multiple regression (e.g., backwards elimination) would overcome the possible problem of non-significant *Bs* by eliminating them.

Time points as data

A problem with regression analysis in the time domain is that the error term is actually the true EEG, which is correlated with itself over time [24]. It has thus been argued that because of this auto-correlation, *B* estimates are unreliable, and that differenced data should be used to overcome the problem [24]. That is, instead of using V_i, the voltage at time *i*, to calculate *B*, '$V_{(i+1)} - V_i$' is used. However, the *B* estimates themselves *are* reliable; it is only the significance values that may be inaccurate when auto-correlation occurs [41]. Further, using differenced data will not solve the problem of auto-correlation [41], and so this innovation is not recommended.

How many EOG channels are required for adequate correction?

Elbert et al. argued that three orthogonal measures are needed to describe eye-movements completely, the vertical, horizontal and radial EOG [14], but other combinations have also been suggested [15, 25]. Most researchers do not use the radial EOG (REOG), and until recently no advantage has been demonstrated in using more than the standard vertical and horizontal EOG [29, 43].

However, using the AAA correction procedure (above), we have recently found in a 15-subject data set employing 19 EEG channels, that correction of both blinks and saccades requires inclusion of the radial channel [12]. Although this is an isolated finding, the results suggest that the radial channel records voltages due to eyelid movement over the globe [30], and that since such eyelid movements are common, they should be accounted for in this way.

What conditions must be met in a calibration trial?

We would suggest that only large vertical, horizontal and blink eye movements are needed, so long as vertical and horizontal movements are orthogonal. It should be noted that having a subject move his eyes 'around' a screen will make VEOG and HEOG correlated, and so it is best to have subjects move their eyes vertically and horizontally from a central point. If an averaging procedure is used, each movement type should be averaged separately to increase the EOG/EEG ratio, with each average's mean DC level subtracted before putting the averages together sequentially and calculating *Bs*. Each eye-movement type average should comprise a minimum of 40 eye-movements [11]. It has been shown that it makes no difference to *B* calculation if we average on a feature of the eye-movement voltage, or on the evoking stimulus as in a traditional ERP experiment [11], so either option can be employed.

Another important aspect is that eye-movements should be paired, such that if an 'up' saccade is used, a 'down' saccade of similar magnitude should also be used. This is because the neural potentials related to a specific eye-movement may distort *Bs* slightly, and this method will cancel out such distortions. Further, it is important to ensure that the recording configuration (e.g., reference, time constant, filter characteristics) is the same for the EOG and EEG channels.

Median, mean or trimmed mean *B*, from subject or group?

If we assume that there is some random error involved in the *B* estimation process, then we can employ statistical means to overcome this. For example, instead of calculating one *B* per site per subject, we could split the data, calculate a number of *Bs*, and use the median *B* for each site. This would minimize the effect of *B* estimate outliers not representative of true propagation. Verleger and co-workers proposed a 'trimmed mean' approach, where the highest and lowest 10% of the *Bs* are ignored [46]. Berg argued for the use of the median *B* [3], and it has also been argued that it was reasonable to use the mean *B* from a number of subjects [17, 46].

The median and trimmed mean approach both appear useful to us, but we would advise against any *B* collation over subjects, because *B* estimates vary as a function of electrode placement and subjects' head dimensions. For instance, between-subject differences have been found at frontal, central and parietal sites [40], and Gasser et al. [18] reported *B* standard deviations at frontal sites ranging from 0.04 to 0.13. We consider this variation too great to validly use any central tendency measure in which *Bs* are collated across subjects.

Issues relating to the correction phase

What error is involved in the correction phase?

It should be noted that even if an accurate correction coefficient is obtained, there can be error in the correction phase [47]. This is because neural potentials propagate forward to the EOG, and so the EOG is composed of (at least) two things, eye-movement voltages and neural potentials, as shown in Eqn. 7. Thus when we subtract a portion (*B*) of EOG from the EEG (Eqn. 3), we are really following Eqn. 8.

$$EOG = EOG_{EYE} + EOG_{NEURAL} \quad (7)$$

$$estTEEG = MEEG - (B^{*}EOG_{EYE}) - (B^{*}EOG_{NEURAL}) \quad (8)$$

By subtracting '$B^{*}EOG_{NEURAL}$' we are subtracting a portion of the neural potentials that we are interested in and reducing the EEG magnitude. This magnitude of error could be calculated if we knew the magnitude of the neural potential, and the proportion of it that reaches the EOG. As we do not know these, an approximation can be calculated if we assume that the source is at a particular EEG electrode. For example, if a neural potential originates at Fpz, then approximately 13% of the potential will be removed in the correction phase [Croft RJ, Barry RJ. "Issues relating to the correction phase of the removal of EOG artifact from the EEG", submited]. This estimation will be inaccurate only in so far as the proportion of neural potential that reaches the EOG is different from the proportion from Fpz.

It is important to note that more EEG is artifactually removed frontally in the 'correction' process, causing artifactual distribution patterns over the scalp. For example, 5 Hz activity may appear smaller frontally than parietally after correction, even when the neural activity is consistent over the scalp.

Methods of reducing 'correction phase' error

Filtering out EOG frequencies above 6 Hz has been suggested as a means of overcoming this problem [49].

This was thought to remove neural potentials because eye-movements were not that fast. However, this does not account for low-frequency neural potentials (such as CNV and the P3 complex) and thus does not solve the problem.

Source localization procedures avoid the problem by estimating the *source* of the neural and ocular generated voltages, and removing from the neural potential source a fraction of the *source* of the ocular artifact, rather than the EOG potential itself [5, 27]. This technique would remove correction phase error, but as was argued earlier, it is only appropriate where an MRI scan is available. Thus its utility is limited.

Another possible solution is 'the approximation adjustment' (TAA), where the amount of EEG distortion caused in the correction phase is estimated, and the EEG is adjusted to account for this [Croft RJ, Barry RJ. "Issues relating to the correction phase of the removal of EOG artifact from the EEG", submitted]. It is based on a number of assumptions that amount to the EOG-to-EEG propagation estimate being a reasonable estimate of EEG-to-EOG propagation. The adjustment is applied to the EEG at a site *after* EOG correction, adjusting the corrected EEG ($estTEEG_i$) at time i according to Eqn. 9. This gives a more refined estimate of true EEG ($TEEG_i$), where the summation is over EOG channels and B is the EOG-to-EEG correction coefficient calculated for that site.

$$TEEG_i = estTEEG_i / (1 - \Sigma B^2 \}) \qquad (9)$$

Given the limitations discussed elsewhere [Croft RJ, Barry RJ. "Issues relating to the correction phase of the removal of EOG artifact from the EEG", submitted], it is estimated that the residual error after using this method would range from 0% where the assumptions are met, to 3% when a potential generated prefrontally is measured frontally. Therefore, we believe that this adjustment is adequate for routine correction. It should be noted that this method has not yet been tested, and the error estimates are based on newly formulated theoretical considerations.

Recommended correction procedure

We believe that the aligned-artifact average procedure (AAA) is the best means of removing interference from data, and thus of obtaining accurate correction coefficients (see 'Aligned-artifact averaging'). The method entails the averaging of a number of eye movements so as to minimize interference in the EOG and EEG channels. However, a revision of this procedure (RAAA) has been necessary because the AAA does not deal adequately with the distinction between blink and non-blink data under certain circumstances. This revised method calculates VEOG, HEOG and REOG *Bs* utilizing a calibration trial, and uses these to correct blink and saccade data together.

The average error incurred by the RAAA has been found to be approximately 1 μV when correcting blinks and large pursuit eye-movements [11]. An example of a correction typically obtained with this method is given in *figure 3*. Here the neural potential resulting from an average of 200 blinks, collapsed over 15 subjects, for C3, Cz and C4 combined, is shown along with the uncorrected EEG and the corresponding scaled VEOG. Note that the early negativity in the corrected waveform does not correspond temporally to the vertical eye-movement. An algorithm describing how to implement the RAAA is given in *appendix A*.

Appendix A. Recommended EOG Correction Algorithm (RAAA).

Preparation	♦ All recording characteristics must be the same as in the experiment proper. ♦ VEOG, HEOG and REOG channels must be used.
Calibration Task A	♦ Make a cross appear at varied locations on the screen in a pseudo-random fashion, once per second, to create large horizontal & vertical eye-movements (>40 of each). ♦ Ask S to follow the cross around the screen.
Calibration Task B	♦ Make a cross flash once per second (>40). ♦ Ask subject to blink when the cross flashes.
Averaging Procedure	♦ For each channel, average data separately for each eye-movement type (-100 to 400ms stimulus onset), remove mean DC level, join these averages end to end ♦ Do as above for blinks.
B (1) Calculation	♦ Calculate VEOG & HEOG *B*s with hierarchical multiple regression for each subject, for each EEG & REOG channel separately, using independent variables VEOG & HEOG.
B (2) Calculation	♦ Remove VEOG & HEOG from EEG and REOG blink data, using *B*s calculated from the last stage, and Eqn. 6. ♦ Calculate REOG *B*s from this corrected blink data using simple regression, for each subject and EEG sites separately (independent variable REOG, dependent variable EEG).
Apply to Raw Data	♦ Correct experimental data using the VEOG, HEOG & REOG *B*s calculated above (Eqn. 6).
Adjust Data	♦ Adjust data for over-correction due to forward propagation using TAA (Eqn. 9).

REFERENCES

1 Anthony BJ. In the blink of an eye: implications of reflex modification for information processing. In: Ackles PK, Jennings JR, Coles MGH, eds. Advances In Psychophysiology. Greenwich: JAI Press; 1985. Vol. 1. p. 167-218.
2 Attias J, Urbach D, Gold S, Shemesh Z. Auditory event related potentials in chronic tinnitus patients with noise induced hearing loss. Hearing Res 1993 ; 71 : 106-13.
3 Berg P. The residual after correcting event-related potentials for blink artifacts. Psychophysiology 1986 ; 23 : 354-64.
4 Berg P. Comments on EOG correction methods. J Psychophysiol 1989 ; 3 : 41-4.
5 Berg P, Scherg M. Dipole models of eye-movements and blinks. Electroencephalogr Clin Neurophysiol 1991 ; 79 : 36-44.
6 Brunia CHM, Möcks J, Van Den Berg-Lenssen M. Correcting ocular artifacts – a comparison of several methods. J Psychophysiol 1989 ; 3 : 1-50.
7 Corby JC, Kopell BS. Differential contributions of blinks and vertical eye movements as artifacts in EEG recording. Psychophysiology 1972 ; 9 : 640-4.
8 Croft RJ, Barry RJ. EOG correction: a new perspective. Electroencephalogr Clin Neurophysiol 1998 ; 107 : 387-94.
9 Croft RJ, Barry RJ. EOG correction: A new aligned-artifact average solution. Electroencephalogr Clin Neurophysiol 1998 ; 107 : 395-401.
10 Croft RJ, Barry RJ. EOG correction: Which regression should we use? Psychophysiology, in press.
11 Croft RJ, Barry RJ. EOG correction: Comparing different calibration methods, and determining the number of epochs required. Electroencephalogr Clin Neurophysiol 2000 ; in press.
12 Croft RJ, Barry RJ. EOG correction of blinks with saccade coefficients: a test and revision of the aligned-artifact average solution. Electroencephalogr Clin Neurophysiol 2000 ; in press.
13 Donchin E, Callaway E, Cooper R, Desmedt JE, Goff WR, Hillyard SA, et al. Publication criteria for studies of evoked potentials (EP) in man. In: Desmedt JE, ed. Attention, voluntary contraction, and event related cerebral potentials (Progress in Clinical Neurophysiology). Basel: Karger; 1977. Vol. 1. p. 1-11.
14 Elbert T, Lutzenberger W, Rockstroh B, Birbaumer N. Removal of ocular artifacts from the EEG – A biophysical approach to the EOG. Electroencephalogr Clin Neurophysiol 1985 ; 60 : 455-63.
15 Fortgens C, DeBruin MP. Removal of eye-movements and ECG from the non-cephalic reference EEG. Electroencephalogr Clin Neurophysiol 1983 ; 60 : 455-63.
16 Gasser T, Sroka L, Möcks J. The transfer of EOG activity into the EEG for eyes open and closed. Electroencephalogr Clin Neurophysiol 1985 ; 61 : 181-93
17 Gasser T, Sroka L, Möcks J. The correction of EOG artifacts by frequency dependent and frequency independent methods. Psychophysiology 1986 ; 23 : 704-12.
18 Gasser TH, Ziegler P, Gattaz WF. The deleterious effects of ocular artefacts on the quantitative EEG, and a remedy. Eur Arch Psychiatry Neurosci 1992 ; 241 : 352-6.
19 Girton DG, Kamiya J. Simple on-line technique for removing eye-movement artifacts from the EEG. Electroencephalogr Clin Neurophysiol 1973 ; 34 : 212-6.
20 Gratton G, Coles MGH, Donchin E. A new method for the off-line removal of ocular artifact. Electroencephalogr Clin Neurophysiol 1983 ; 55 : 468-84.
21 Gratton G, Coles MGH. Generalization and evaluation of eye-movement correction procedures. J Psychophysiol 1989 ; 3 : 14-6.
22 Gratton G. Dealing with artifacts: The EOG contamination of the event-related brain potential. Behav Res Meth Instr Comp 1998 ; 30 : 44-53.
23 Hillyard SA, Gallambos R. Eye-movement artifact in the CNV. Electroencephalogr Clin Neurophysiol 1970 ; 28 : 173-82.
24 Jervis BW, Ifeachor EC, Coelho M. The removal of ocular artifacts from the EEG. J Psychophysiol 1989 ; 3 : 16-20.
25 Jervis BW, Nichols MJ, Allen EM, Hudson NR, Johnson TE. The assessment of two methods for removing eye-movement artefact from the EEG. Electroencephalogr Clin Neurophysiol 1985 ; 61 : 444-52.
26 Kenemans JL, Molenaar PCM, Verbaten MN, Slangen JL. Removal of the ocular artifact from the EEG: a comparison of time and frequency domain methods with simulated and real data. Psychophysiology 1991 ; 28 : 114-21.
27 Lins OG, Picton TW, Berg P, Scherg M. Ocular artifacts in EEG and event related potentials. II. Source dipoles and source components. Brain Topography 1993 ; 6 : 65-78.
28 Low MD, Borda RP, Frost JD, Kellaway P. Surface-negative, slow-potential shift associated with conditioning in man. Neurology 1966 ; 16 : 771-82.
29 Lutzenberger W, Elbert T. An attempt of EOG correction. J Psychophysiol 1989 ; 3 : 29-34.
30 Matsuo F, Peters JF, Reilly EL. Electric phenomena associated with movements of the eyelid. Electroencephalogr Clin Neurophysiol 1975 ; 34 : 212-6.
31 Miller GA, Gratton G, Yee CM. Generalized implementation of an eye-movement correction procedure. Psychophysiology 1988 ; 25 : 241-3.
32 Möcks J, Gasser T, Sroka L. Approaches to correcting EOG artifacts. J Psychophysiol 1989 ; 3 : 21-6.
33 Nunez P. Electric fields of the brain: the neurophysics of EEG. New York: Oxford University Press; 1981.
34 O'Toole DM, Iacono WG. An evaluation of different techniques for removing eye- blink related artifact from the visual evoked response recordings. Psychophysiology 1987 ; 24 : 487-97.
35 Overton DA, Shagass C. Distribution of eye-movement and eyeblink potentials over the scalp. Electroencephalogr Clin Neurophysiol 1969 ; 27 : 546.
36 Putnam LE, Roth WT. Effects of stimulus repetition, duration, and rise time on startle blink and automatically elicited P300. Psychophysiology 1990 ; 27 : 275-97.
37 Quilter PM, McGillivray BB, Wadbrook DG. The removal of eye movement artifact from the EEG signals using correlation techniques. Random Signal Analysis, IEEE Conference Publication 1977 ; 159 : 93-100.
38 Rockstroh B, Elbert T, Birbaumer N, Lutzenberger W. Slow brain potentials and behavior. Baltimore: Urban and Schwarzenberg; 1982. p. 55-7.
39 Rowland V. Cortical steady potential (direct current potential) in reinforcement and learning. Prog Physiol Psychol 1968 ; 2 : 1-77.
40 Semlitsch HV, Anderer P, Schuster P, Presslich O. A solution for reliable and valid reduction of ocular artifacts, applied to the P300. Psychophysiology 1986 ; 23 : 695-703.
41 Tuan PD. A comment from the viewpoint of time series analysis. J Psychophysiol 1989 ; 3 : 46-8.
42 Van Den Berg-Lenssen MMC, VanGisbergen JAM, Jervis BW. Comparison of two methods for correcting ocular artefacts in EEGs. Med Biol Engin Comp 1994 ; 32 : 501-11.

43 Van Den Berg-Lenssen MMC, Brunia CHM, Blom JA. Correction of ocular artifacts in EEGs using an autoregressive model to describe the EEG; a pilot study. Electroencephalogr Clin Neurophysiol 1989 ; 73 : 72-83.
44 Van Driel G, Woestenburg JC, Van Blokland-Vogelesang AW. Frequency domain methods: a solution for the problems of EOG-EEG contamination in ERPs. J Psychophysiol 1989 ; 3 : 29-34.
45 Verleger R. The instruction to refrain from blinking affects auditory P3 and N1 amplitudes. Electroencephalogr Clin Neurophysiol 1991 ; 78 : 240-51.
46 Verleger R, Gasser T, Möcks J. Correction of EOG artifacts in event- related potentials of the EEG: aspects of reliability and validity. Psychophysiology 1982 ; 19 : 472-80.
47 Vigario RN. Extraction of ocular artefacts from EEG using independent component analysis. Electroencephalogr Clin Neurophysiol 1997 ; 103 : 395-404.
48 Weerts TC, Lang PJ. The effects of eye fixation and stimulus and response location on the contingent negative variation (CNV). Biol Psychol 1973 ; 1 : 1-19.
49 Whitton JL, Lue F, Moldofsky H. A spectral method for removing eye movement artifacts from the EEG. Electroencephalogr Clin Neurophysiol 1978 ; 44 : 735-41
50 Woestenburg JC, Verbaten MN, Slangen JL. The removal of the eye-movement related artifact from the EEG by regression analysis in the frequency domain. Biol Psychol 1983 ; 16 : 127-47.