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Time-frequency Analysis of Eye Blinks and Saccades in EOG for EEG Artifact Removal

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Abstract— **The electro-oculogram (EOG) is commonly used to detect, reject and remove ocular artifacts (OAs) from the electroencephalogram (EEG). We present a new time-frequency analysis of OAs found in the EOG. Our results indicate that in some tasks and subjects, frequencies up to 181Hz exist. Based on these results, we propose a minimum sampling rate for EOG. In addition, since EOG measurements typically contain signals other than OAs (including underlying EEG), we propose an alternate measurement of OAs based on a video-based eye tracker, and suggest a minimum frame rate for the use of such devices.**

I. Introduction

Eye movements and blinks pose a serious problem for electroencephalogram (EEG) measurements, and their removal from measured EEG is an ongoing research problem [1][2][3][4]. Almost all current approaches to ocular artifact (OA) detection and removal [5][6][7] use one or more electro-oculogram (EOG) signals either directly or indirectly as a reference.

For clinical EEG and other EEG applications (e.g., brain-computer interfaces or BCIs), collecting EOG is relatively simple and inexpensive. Detection of large OAs (e.g., blinks) can be accomplished using simple threshold operators, while OA removal can be accomplished using more sophisticated methods such as blind source separation [8][9]. However, the EOG signal contains not only eye movements and blinks, but also neural sources [10] (including those seen at EEG electrodes) and other sources of artifacts such as facial twitches. Also, during a blink or large eye movement, EOG electrodes move along with the facial muscles around the eyes, introducing additional noise in the measurement.

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For applications where parts of the EEG can be simply rejected, and there is no restriction about placing extra electrodes on the subject's face, the EOG may be used to detect most eye movements and mark portions of the EEG to reject, assuming the EOG is filtered and sampled appropriately. For many applications, however, it is unacceptable to discard large portions of the EEG. In those cases, since the EOG may contain part of the EEG of interest, using the EOG as a reference in the OA removal scheme runs the risk of distorting the EEG after artifact removal. For other, real-world applications (e.g., BCIs), it is highly desirable (and sometimes even a requirement) not to place extra electrodes on the subject's face. Thus alternative ways of measuring eye movements and blinks should be explored as possible references for the removal of OAs from EEG.

One such alternative is a non-contact video-based eye tracking device (ETD). Unlike EOG, these devices do not require anything to be attached to the subject's face or head, and can be used to extract only eye movements and blinks. Since their measurement is not contaminated with any other biological sources, they can be used as a source for OA removal without significantly distorting the underlying EEG of interest. While such a device introduces an extra piece of equipment, it can simultaneously provide the point-of-gaze of the subject, which can be very useful in a clinical EEG experiment or BCI. However, in order to select an appropriate ETD, the time-frequency characteristics of the EOG must first be analyzed to ensure that the ETD is capable of providing output at a rate that at least matches the highest frequency in the EOG. Where the addition of an ETD is not possible or cannot be justified for the given application (e.g, simple OA rejection), such an analysis is essential in order to select appropriate filtering and sampling parameters for the EOG.

While some work has been done to analyze the frequency components of various OAs in the EEG, there has been little work to show the time-frequency characteristics of specific types of OAs in the original EOG. Even the few studies [11][12][13][14] that have examined the frequency content at EEG sites do not analyze higher frequency components. Also, since neither neural nor ocular signals are stationary, it is inappropriate to use simple spectral analysis. Instead, a time-frequency analysis (e.g., spectrogram or short-time Fourier transform) is more appropriate [15].

This paper provides a time-frequency analysis of blinks and eye movements (specifically large, rapid eye movements or "saccades") in an EOG signal measured at a very high sampling rate. Based on the analysis, we suggest minimum filtering and sampling frequencies needed for EOG to avoid missing eye movements and blinks that may cause artifacts in the EEG. In addition, a minimum sampling rate for an eye tracker-based alternative for OA removal is suggested.

II. Methods

Data was collected from 3 subjects (one male, two female, all between the ages of 20-35), sitting approximately 50cm in front of a computer monitor. EOG electrodes were attached at the right outer canthus and nasion for horizontal EOG (HEOG) measurement, and above and below the right eye for vertical EOG (VEOG). Both signals were amplified with an amplifier having a nominal gain of 1100, equipped with a second-order Butterworth low-pass filter with a cutoff frequency of 12kHz. The data was sampled at 24.5kHz using a PC and 12-bit analog to digital converter board.

Each subject was instructed to perform four tasks. During the first task, a 4x4 grid of numbers was displayed on the computer monitor. Each number was sequentially highlighted for two seconds, and the subject was instructed to follow the highlighted number. The data from this task was used to analyze involuntary blinks. During the second task, the same grid was shown, but this time the subject was instructed to blink at least once during a two second interval. The data from this task was used to analyze voluntary blinks. Seven trials of 32 seconds each were collected from each subject for the first and second tasks. During the third task, a small red dot was shown sequentially for one second on each corner of the computer monitor, and the subject was instructed to follow the dot. Twenty-five trials for a total of 100 seconds of data were collected from each subject, and the data from this task was used to analyze medium-sized saccades. During the final task, the subject was instructed to look at the ceiling, at the floor and back up at the ceiling five times in a row, and then to look to the far left, the far right and again the far left five times in a row. Each eye movement was guided to last about two seconds. The entire trial was repeated five times for each subject, and the data from this task was used to analyze large saccades.

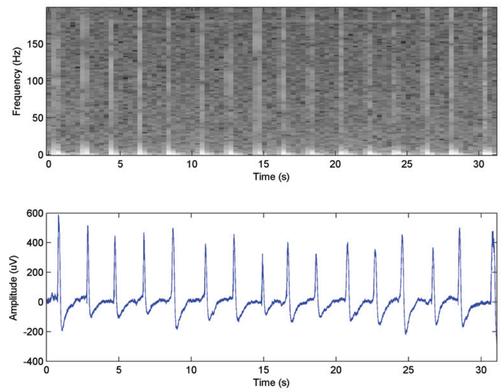
Once the two EOG signals (VEOG and HEOG) were digitized, two digital filters were applied to each signal: a 60Hz notch filter to remove line noise, and a 1000Hz 2nd-order Butterworth low-pass filter. The spectrogram of each signal was then calculated using a Hanning window. After visual inspection of several trials, it was determined that no significant power existed beyond 200Hz for any of the collected data. Thus, for each time epoch in the spectrogram, the power in the 0.1-200Hz range was examined (see Figure 1 for an example). For each time epoch, a frequency f was calculated such that the power in the 0-f Hz range contains 25% of the total power. Similarly, the frequencies containing 50% and 95% of the total power were calculated for each time epoch.

			Blinks			***Saccades***		
			25%	50%	95%	25%	50%	95%
Subject 1	**VEOG**	**min**	0.0	0.0	1.5	0.0	0.0	1.5
		max	1.5	6.0	140.6	1.5	9.0	134.6
		mean	0.4	1.1	22.6	0.2	0.8	16.2
	HEOG	**min**	0.0	0.0	1.5	0.0	0.0	1.5
		max	4.5	35.9	179.5	1.5	3.0	130.1
		mean	0.8	3.1	57.5	0.3	0.7	16.4
Subject 2	**VEOG**	**min**	0.0	0.0	1.5	0.0	0.0	1.5
		max	1.5	19.4	181.0	1.5	1.5	179.5
		mean	0.2	1.1	20.3	0.1	0.4	12.1
	HEOG	**min**	0.0	0.0	1.5	0.0	0.0	1.5
		max	3.0	44.9	178.0	3.0	3.0	116.7
		mean	0.5	2.5	50.8	0.2	0.4	7.9
Subject 3	**VEOG**	**min**	0.0	0.0	1.5	0.0	0.0	1.5
		max	23.9	46.4	121.2	3.0	3.0	86.8
		mean	3.0	8.6	53.6	0.2	0.5	9.4
	HEOG	**min**	0.0	0.0	1.5	0.0	0.0	1.5
		max	10.5	44.9	166.1	3.0	4.5	98.7
		mean	0.7	3.0	52.4	0.2	0.4	7.4
Total	**VEOG**	**min**	0.0	0.0	1.5	0.0	0.0	1.5
		max	23.9	46.4	**181.0**	3.0	9.0	179.5
		mean	1.4	4.2	34.9	0.2	0.6	**12.6**
	HEOG	**min**	0.0	0.0	1.5	0.0	0.0	1.5
		max	10.5	44.9	179.5	3.0	4.5	130.1
		mean	0.7	2.9	**54.2**	0.2	0.5	11.0

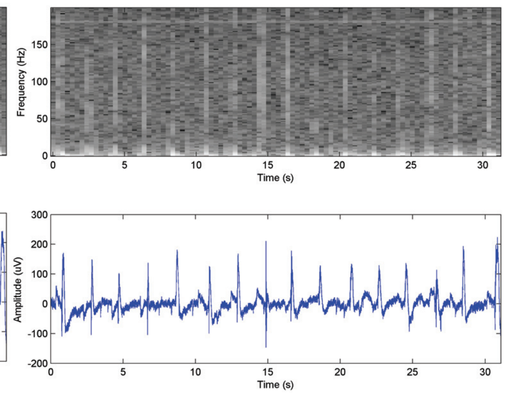
Table 1: Frequencies required to capture 25%, 50% and 95% of the power at any given time for blinks (voluntary and involuntary) and saccades (medium and large) as measured by the EOG.

III. Results

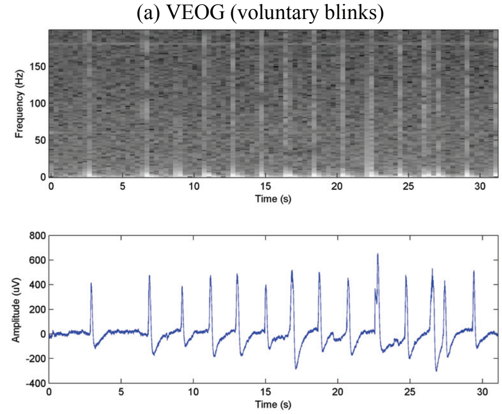
The minimum and maximum frequencies containing 25%, 50% and 95% of the power at any given time epoch in the spectrogram, and the average frequency over all epochs containing 25%, 50% and 95% of the power were calculated over all trials for each subject and for each task. The results are shown in Table 1 for blinks (voluntary and involuntary) and for saccades (medium and large). From Table 1, it appears that there is a notable difference between the frequency content of blinks and saccades. A t-test showed that the mean frequency required to account for 95% of the power over all subjects is statistically significantly different ($p<.05$) between blinks and saccades. The data also shows that frequencies as high as 181Hz need to be considered to account for 95% of the power for a particular subject and task. Similarly, on average over all subjects, frequencies up to 54Hz for blinks and up to 13Hz for saccades must be considered to account for 95% of the power at any given time.



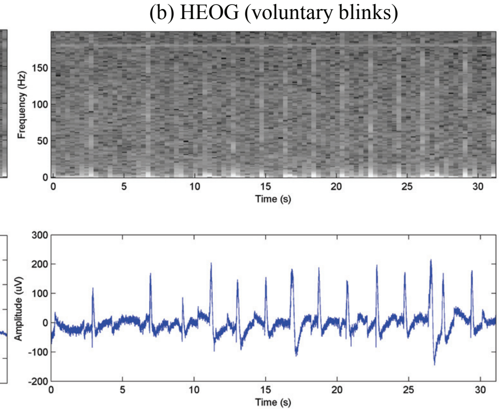
(a) VEOG (voluntary blinks)



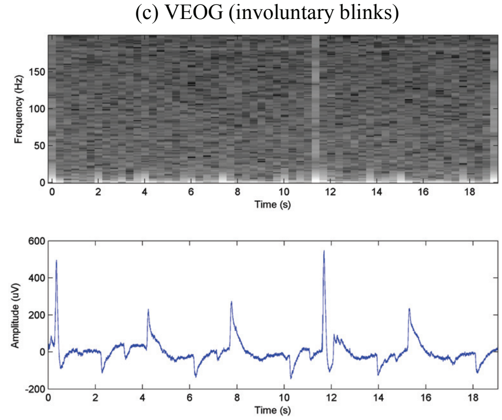
(b) HEOG (voluntary blinks)



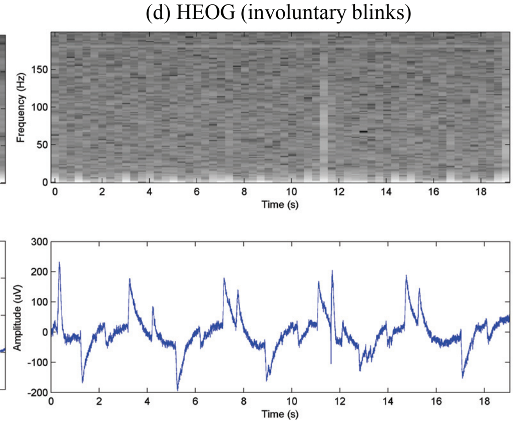
(c) VEOG (involuntary blinks)



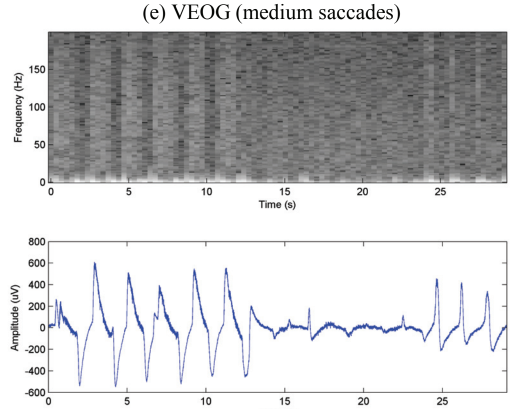
(d) HEOG (involuntary blinks)



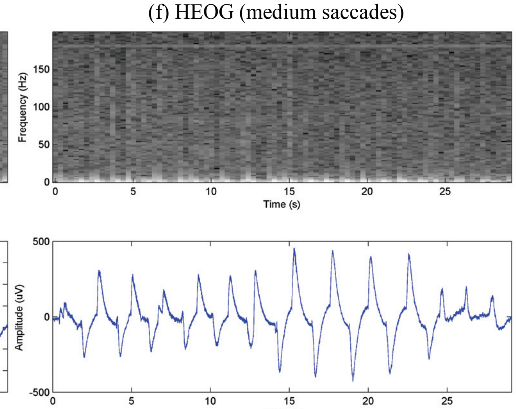
(e) VEOG (medium saccades)



(f) HEOG (medium saccades)



(g) VEOG (large saccades)



(h) HEOG (large saccades)

Figure 1: Sample measured VEOG, HEOG and corresponding spectrograms for each task for a single subject. Gray levels in spectrogram represent power spectral density (dB) at the corresponding time epoch and frequency, with brighter values representing a higher power spectral density.

Table 2 compares mean frequencies for voluntary and involuntary blinks and for medium and large saccades. It appears that there is no substantial difference in frequency content between medium and large saccades, but that there may be some difference in the frequency content between voluntary and involuntary blinks. A t-test revealed that the mean frequency required to account for 95% of the power over all subjects is statistically significantly different ($p<.05$) between voluntary and involuntary blinks in both VEOG and HEOG and between medium and large saccades in HEOG but not in VEOG.

Figure 1 shows a sample of the measured VEOG, HEOG and spectrogram for each task for a single subject. In this figure it can be seen that the amplitude of the VEOG and HEOG signals for saccades vary widely over time. At times they are similar to amplitudes for blinks. Although the propagation of blinks and saccades to EEG electrode sites may be different, this suggests that saccades should not be ignored for effective OA removal.

	Power	25%	50%	95%
Large saccades	**VEOG**	0.2	0.6	11.6
	HEOG	0.2	0.4	7.5
Medium saccades	**VEOG**	0.2	0.6	13.4
	HEOG	0.3	0.6	13.6
Involuntary blinks	**VEOG**	2.1	6.0	43.1
	HEOG	0.7	3.4	62.7
Voluntary blinks	**VEOG**	0.8	2.4	26.7
	HEOG	0.7	2.5	45.7

Table 2: Comparison of frequencies required, on average, to capture 25%, 50% and 95% of the total power at any given time instant for each of the four tasks.

IV. CONCLUSIONS

We found that saccades can have amplitudes approaching those of blinks in the EOG. Further research is required to see if the same holds at EEG electrode sites. In addition, on average over all subjects (Table 1), frequencies up to 54Hz need to be considered to account for 95% of the power. Our results further indicate that frequencies as high as 181Hz can appear in a subject's EOG during certain tasks. This suggests that if EOG is used in an EEG ocular artifact removal scheme, it should be filtered below 181Hz and sampled at least at 362Hz to avoid aliasing. In addition, if as we suggested above, a video-based eye tracking device is used instead of the EOG to remove ocular artifacts, it would need to provide eye tracking output at a frequency of at least 362Hz.

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