Brain Activity in Virtual Reality: Assessing Signal Quality of High-Resolution EEG While Using Head-Mounted Displays

Category: Methodological

ABSTRACT

Biometric measures such as the electroencephalogram (EEG) promise to become viable alternatives to subjective questionnaire ratings for the evaluation of psychophysical effects associated with Virtual Reality (VR) systems, as they provide objective and continuous measurements without breaking the exposure. The extent to which the EEG signal can be disturbed by the presence of VR systems, however, has been barely investigated. This study outlines how to evaluate the compatibility of a given EEG-VR setup on the example of two commercial head-mounted displays (HMDs), the Oculus Rift and the HTC Vive Pro. We use a novel experimental protocol to compare the spectral composition between conditions with and without an HMD present during an eyes-open vs. eyes-closed task. We found general artifacts at the line hum of 50 Hz, and additional HMD refresh rate artifacts (90 Hz) for the Oculus rift exclusively. Frequency components typically most interesting to non-invasive EEG research and applications (<50 Hz), however, remained largely unaffected. We observed similar topographies of visually-induced modulation of alpha band power for both HMD conditions in all subjects. Hence, the study introduces a necessary validation test for HMDs in combination with EEG and further promotes EEG as a potential biometric measurement method for psychophysical effects in VR systems.

1 INTRODUCTION

Psychophysical effects, such as Presence and Virtual Body Ownership (VBO), are systematically generated and used to facilitate VR applications in a variety of areas, while undesired effects like cybersickness have to be kept to a minimum [1]. An extensive repertoire of methods for measuring these effects exists that allows to compare alternative implementations and to draw conclusions about how to increase the effectiveness of specific VR systems. Among these, the aforementioned effects are often evaluated via subjective questionnaire ratings, which can be biased due to item ambiguity and complexity of questions [2]. Furthermore, questioning during the exposure can break the immersion [3], whereas questioning after the immersion relies on retrospective recalls [2]. Objective measures, such as recording brain activity, do not exhibit these drawbacks. Compared to non-neural physiological metrics, these methods provide several potential advantages and are also the only approach to sample the origin of these effects, providing insights into the validity of the associated theoretical frameworks. Electroencephalography (EEG) in particular is a good fit for joint VR experiments as it is non-invasive, relatively nonrestrictive and offers high temporal resolution [4]. Aided through the increased availability of head-mounted displays (HMDs), studies employing both VR and EEG have recently gained considerable traction over a wide range of research topics. Presence in VEs, for instance, has already been assessed in EEG experiments [5]. Despite this, the influence of active HMDs on EEG signals has not been conclusively evaluated. EEG is susceptible to artifacts of various origins, e.g., the electrical grid [6], and while sporadic studies exist [7], studies combining on commonly used high-end HMDs and high resolution EEG devices are lacking. Therefore, we designed a study to examine the EEG signal quality obtained with a high-resolution EEG system while using active HMDs, based on the example of two prominent products, the Oculus Rift (henceforth ”Oculus”) and the HTC Vive Pro (henceforth ”Vive”). Our findings detail methods of assessing compatibility of system components and serve as a basis for further optimization of concurrent EEG-VR settings.

2 EVALUATION

We employed a 2 x 2 experiment design: Two conditions, ”VR” and ”No-VR” with HMDs present or not, respectively, and two tasks to induce physiological modulation of brain oscillations via the ”Berger Effect” [8], cueing the subjects to either open or close their eyes. For ”No-VR”, the subjects were seated in a dimly lit room facing a wall showing a fixation cross. For ”VR”, a virtual model of the experimental environment was presented via the Oculus for all subjects and additionally via the Vive for subject 4 and 5. Tasks were cued pseudo-randomly via controller vibration to be performed for 10 seconds, aiming for 50 trials per condition. The sequence both conditions was varied over subjects. EEG data and task cues were synchronized and recorded via lab streaming layer [9]. EEG was acquired from 64 scalp positions (NeurOne Tesla, Mega Electronics Ltd, Kuopio, Finland) using a wet-gel electrode EEG cap (WaveGuard Touch, eemagine, Berlin, Germany), aiming for impedance values below 5 kΩ and sampling at 5 kHz. Data analysis was performed in MATLAB [10]. We applied a 0.1 Hz High-Pass filter subsequently averaged to a common-average reference. Electrodes Fz, F1 and F2 were excluded due to mechanical interference with the HMDs, while mastoid electrodes were excluded due to high impedance. To compare the frequency responses between VR and No-VR conditions, we calculated the power spectrum over a frequency range from 1 Hz to 2.5 kHz. Spectral analysis was based on the built-in Fast Fourier Transform function. All power spectra reflect the median over trials of a given condition. To investigate the differences in the alpha band (8 Hz-13 Hz) related to the eyes-open and -closed conditions, relative spectra were calculated by dividing the ”closed” power by the ”open” power baseline. To account for inter-subject variability of maximum alpha power, the alpha band data was calculated as the across-frequency median for the individual maximum alpha power peak frequency +/- 2 Hz. We tested six subjects (age range: 23–36 years, median: 24 years, 3 male). Subjects were healthy and did not suffer from neurological or psychological conditions, and gave their informed consent. The study was approved by the Ethics committee of the university of the authors.

3 RESULTS

Comparing across-trial median power over frequency for eyes-closed trials in VR (red) and No-VR (blue) conditions, we found that while the general typical 1/f slope of the curves matched across conditions, we find sharp peaks in frequencies >50 Hz for measurements with the Oculus that were absent in No-VR measurements. This effect was especially pronounced in very high frequencies (>100 Hz). The overall curve shape in the lower frequencies in both VR and No-VR conditions was very similar in our measurements (see figure 1). This includes pronounced peaks around 10 Hz for eyes-closed measurements (see figure 1 A, C, E), which was less prominent in the corresponding eye-open curves. We further observed strong 50-Hz peaks in all measurements as well as associated harmonics. In signals acquired in joint recordings with the Oculus, we also detected prominent, high-amplitude spectral peaks in frequencies above 100

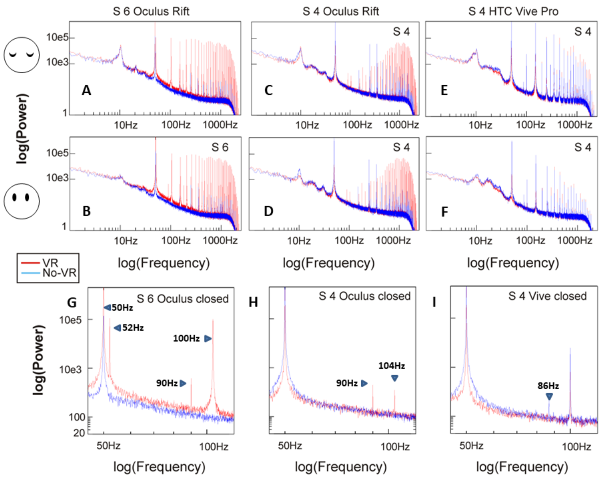

Figure 1: Detailed spectral power distribution for electrode Cz: Subfigures (A) to (I) display examples for the spectral power over frequency at electrode Cz (the centermost electrode) for different measurements. A,C and E show across-trial median eyes-closed results, B,D and F show eyes-open results in from 1 - 2500 Hz. G,H and I display eyes-closed results from 45 - 120 Hz for subject 6 using a Oculus, subject 4 also using a Oculus and subject 4 using the Vive. We find the most pronounced amplitude peaks around 50 Hz. Around 10 Hz, high amplitudes exist in all eyes-closed data compared to their eyes-open equivalent (e.g., A and B). (G) shows an example of 90 Hz peaks for the VR condition. Results for VR are red and blue for No-VR. For all subfigures, the x- and y-axis respectively denote frequency (Hz) and spectral power (μV^2) logarithmically.

Hz (figure 1 A to D) as well as distinct peaks at 52 Hz and 90 Hz, in contrast to the measurements with the Vive (1 E and F). Generally, spectral responses between VR and No-VR matched much more closely for measurements with the Vive, even in the higher end of the frequency range. We further calculated relative spectral power (eyes-closed vs. eyes-open conditions) in the alpha band. The topographical power distribution showed enhanced alpha band power in occipital areas. Within each of the investigated subjects, this effect showed very similar topographies both conditions.

4 DISCUSSION

The main finding of the present study is that the signal quality of EEG measurements in combination with two contemporary HMDs remains largely unaffected in frequencies below approx. 50 Hz compared to the frequency range above. This range includes the signal components most relevant to contemporary EEG studies. We generally found strong artifacts around 50 Hz and harmonics thereof, which are caused by the electric grid [6] and are typically dealt with by using a Notch filter. In higher frequencies, signals recorded while using the Oculus showed sharp spectral peaks at 90 Hz and its harmonics, that were not present without the HMD. This is likely caused by the device's refresh-rate, which is set at 90 Hz [11]. Flicker stimulation EEG studies have shown that pulsed visual stimulation can elicit steady-state neural oscillations in frequencies up to 90 Hz, although the effect is stronger in lower frequencies and more pronounced in occipital electrodes [12], which we did not find in our data. Thus we assume a neural response as less likely and propose a direct electromagnetic artifact. Further phantom head measurements are necessary to distinguish between both explanations. We further found robustly increased alpha band power in eyes-closed measurements in all conditions, particularly in occipital electrodes. This "Berger Effect" [8] is well established to reflect modulation of cortical neural population activity, thus serving as a good benchmark to compare signal quality between VR and No-VR experiments. The distribution of spectral peak of alpha activity was consistent both within and across subjects as well as between devices, demonstrating the feasibility of meaningful EEG-based brain mapping while wearing a HMD. Note that we only used a single device for each of the two HMD products as examples. Thus, experiments involving different devices, models or generations might influence the EEG signal in different ways, highlighting the general necessity to validate the EEG signal quality in a specific setup for joint measurements with HMDs.

5 CONCLUSION

Our work demonstrates the usefulness of assessing EEG signal quality for experiments joining EEG and HMDs, based on the example of two current HMD models, where we find the signal mainly affected in frequencies above 50 Hz, mostly sparing the lower frequency range that is leveraged in the vast majority of contemporary non-invasive EEG studies. However, techniques such as independent component analysis (ICA) and HMDs optimized for EEG-compatibility could be highly useful for clearing EEG data from HMD-related artifacts and thus enable more high-quality measurements in higher frequencies. As commercial HMDs are subject to ongoing developments, it is advisable to validate future joint implementations as to ensure the sensible interpretation of physiological correlates of psychophysical effects.

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