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The effect of monitor raster latency on VEPs, ERPs and Brain–Computer Interface performance

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HIGHLIGHTS

- The monitor raster latency causes a time shift of VEPs and ERPs.
- A method for correcting the monitor raster latency is proposed.
- BCI performance can be increased significantly by correcting the raster latency.

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ABSTRACT

Background: Visual neuroscience experiments and Brain–Computer Interface (BCI) control often require strict timings in a millisecond scale. As most experiments are performed using a personal computer (PC), the latencies that are introduced by the setup should be taken into account and be corrected. As a standard computer monitor uses a rastering to update each line of the image sequentially, this causes a monitor raster latency which depends on the position, on the monitor and the refresh rate.
New method: We technically measured the raster latencies of different monitors and present the effects on visual evoked potentials (VEPs) and error-related potentials (ERPs). Additionally we present a method for correcting the monitor raster latency and analyzed the performance difference of a code-modulated VEP BCI speller by correcting the latency.
Comparison with existing methods: There are currently no other methods validating the effects of monitor raster latency on VEPs and ERPs.
Results: The timings of VEPs and ERPs are directly affected by the raster latency. Furthermore, correcting the raster latency resulted in a significant reduction of the target prediction error from 7.98% to 4.61% and also in a more reliable classification of targets by significantly increasing the distance between the most probable and the second most probable target by 18.23%.
Conclusions: The monitor raster latency affects the timings of VEPs and ERPs, and correcting resulted in a significant error reduction of 42.23%. It is recommend to correct the raster latency for an increased BCI performance and methodical correctness.

1. Introduction

In the field of visual neuroscience as well as for Brain–Computer Interfaces (BCIs) (Wolpaw et al., 2000), experiments based on visual stimuli are often required to have a strict timing in a millisecond scale. For example, if a experiment presents visual stimuli and the subject has to push a button in order to measure the reaction time, it is required to know the exact timing of both the stimulus and the button press, generally this is done by storing timestamps. If there are any latencies, they have to be corrected, otherwise the results will be distorted leading to wrong conclusions like measured reaction times are longer as they really are.

For many BCIs, which are used to perform computer commands based on brain activity, exact timings are crucial, too. For instance, the electroencephalogram (EEG) of the brain's response to a visual stimulus, the visual evoked potential (VEP) (Sutter, 1984), is one commonly used method for BCI control (Spüler et al., 2012b; Chen et al., 2015) and it is required to know the exact timings of stimuli presentation, as the brain responds in a millisecond scale. If stimuli timings vary, VEPs will be time shifted corresponding to that

Abbreviations: CRT, cathode ray tube; LCD, liquid crystal display; OLED, organic light emmiting diode; OCSVM, one class support vector machine.

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variation. Recent studies have shown that latencies of P300 event-related brain potentials (ERP) and error-related potentials (ErrPs) vary depending on the experiment (Gonsalvez and Polich, 2002; Iturrate et al., 2014) and that correcting latencies leads to a better generalization (Iturrate et al., 2014) and an increased performance (Mowla et al., 2017).

As shown by Wilson et al. (2010) a personal computer (PC) system has several potential factors which cause latencies, for example the system latency of the operating system, the video output latency, or the monitor input lag. Since most experiments use PCs for stimulus presentation and data analysis, those latencies should be taken into account. They also showed that several other factors exist especially for BCIs. They used BCI2000 (Schalk et al., 2004) a general-purpose software system for BCI control and measured latencies caused by the amplifier, the software signal processing and other factors. If the factors which cause more or less static latencies are known, they can be corrected easily by fixing the timestamps or by shifting the data, respectively. Contrary to static latencies, varying latencies (jitter) can dramatically alter the results and are harder to handle, as it is required to know how latencies vary and the data must be corrected accordingly. If the jitter will not be corrected, it could lead to a distortion of results.

One latency causing factor is yet mostly unconsidered: the monitor rater latency. Experiments using a monitor for stimulus presentation should consider the fact how a monitor will present each single frame. A frame will be presented line-wise from top to bottom, resulting in an increasing latency from the upper left pixel to the bottom right pixel, the raster latency. More precisely, the latencies are based on the addressing scheme of the monitor. For example, a cathode ray tube (CRT) monitor presents the pixels from left to right and top to bottom, furthermore a CRT scan can be uninterlaced (first line to last line) or interlaced (odd lines first followed by even lines). Liquid crystal displays (LCDs) and organic light emitting diode (OLED) displays generally present a frame line by line (Pappas et al., 2009). Regardless of the display technique, the total processing time of each frame is approximately 95% of the inverse of the refresh rate. For a refresh rate of 60 Hz, there will be a delay of $0.95/60 = 15.8\bar{3}$ ms between the first and the last pixel of that frame, as shown by Elze (2010). This property of a monitor, that leads to varying latencies, are attended by some researchers in the field of neuroscience (Garaizar et al., 2014), but does not seem to get much attention in visual BCI experiments.

All BCIs using a standard monitor will be effected by the raster latency regardless of whether they are based on code-modulated VEPs (Spüler et al., 2012b), steady-state VEPs (Chen et al., 2015), P300 (Panicker et al., 2011), or ErrPs (Spüler et al., 2012a).

In this paper, we first measure the raster latencies on different monitors. Afterwards, we present the influence of the raster latency on SSVEP, cVEP and P300. Based on the cVEP BCI, we present a method that corrects for the raster latencies and show that BCI performance can be significantly improved by taking the raster latency into account.

2. Material and methods

2.1. Measuring raster latencies

In order to determine the raster latencies, we measured them on an old CRT monitor (Iiyama A901HT), an old LCD monitor (Dell 1908FPc) and a new LCD monitor (BenQ XL2430-B) of the year 2016 using the latest technology with low reaction times. The presentation layer was implemented in MATLAB (2016) using the Psychtoolbox-3 (Brainard and Vision, 1997). A stimulus was presented once each second on the full screen size for the length of one refresh cycle of the monitor. Since the refresh rate was set to 60 Hz, each stimulus had a length of $16.\bar{6}$ ms. The parallel port was used as the trigger and was set right after the `Screen('Flip', ...)` command, which should – theoretically – present the stimulus immediately at the start of a refresh cycle if there were no latencies at all. The time at which the stimulus was presented on the monitor was determined by a photodiode which was held once at the top left and once at the bottom right position of the monitor. To measure the timings we used an oscilloscope (Rohde&Schwarz HMO1022) with a sampling rate of 25 kHz. We repeated all measures 5 times for each monitor.

As the measured voltage of the parallel port switch immediately between states, it is easy to determine the onset time which represents the theoretical stimulus onset time. The monitors need a specific amount of time till full illumination is reached, because of this and the fact that the photodiode has a small jitter we specified the real stimulus onset time of the monitors as the time point at which 100 successive samples (4 ms window) are above the mean baseline.

2.2. Analysis of SSVEP data

We implemented a simple SSVEP experiment to determine the effects of the measured raster latencies in the brains response.

Setup. The setup consisted of an g.USBamp (g.tec, Austria) EEG amplifier, a PC and the LCD monitor (BenQ XL2430-B) mentioned above. The presentation of the stimuli was operated from the PC and synchronized with the EEG amplifier by using the parallel port. BCI2000 (Schalk et al., 2004) was used as a general framework for recording the data of the 32 electrodes, from which 30 were located at Fz, T7, C3, Cz, C4, T8, CP3, CPz, CP4, P5, P3, P1, Pz, P2, P4, P6, PO9, PO7, PO3, POz, PO4, PO8, PO10, O1, POO1, POO2, O2, OI1h, OI2h, and Iz. The remaining two electrodes were used for electrooculography (EOG), one at the nasal bridge and one at the outer canthus of the left eye. The ground electrode (GND) was positioned at FCz and reference electrode (REF) at OZ. The monitor refresh rate was set to 60 Hz and the amplifier sampling rate to 600 Hz, resulting in 10 samples per frame.

Experimental design. The stimuli were presented at the top left and bottom right area of the monitor, to evaluate the full magnitude of raster latencies caused by the monitor. The Psychtoolbox-3 was used to present a 5 cm × 5 cm square to the subject with a stimulation rate of 1 Hz and 15 Hz, respectively. Each stimulus was presented for one frame, resulting in a stimulus length of $16.\bar{6}$ ms.

To avoid fatigue, a run consists of 4 parts with 2 min each: (1) 1 Hz top left position, (2) 1 Hz bottom right position, (3) 15 Hz top left position, and (4) 15 Hz bottom right position. In total the subject had to perform 3 runs, therefore, we got 6 minutes of EEG data for each part.

Processing. The EEG data was notch-filtered by the amplifier at 50 Hz and additionally to increase the signal-to-noise ratio a 200th-order bandpass finite impulse response filter was applied between 0.1 Hz and 30 Hz. To avoid a phase shift due to the filtering, we used the MATLAB `filtfilt` function which performs a zero-phase digital filtering.

We analyzed the EEG data of electrode O2 by averaging over windows of 1 s length, resulting in $6 \cdot 60 = 360$ windows for each of the 4 parts. To determine the time shift between the top-left and bottom-right position, the cross-correlation was used. These results in the number of shifted samples at which the VEP responses correlate most, which in turn can be converted to the time shift.

2.3. Analysis of P300 data

Setup. The P300 data used for latency estimation were recorded in a previous study (Spüler et al., 2012a), in which 24 subjects