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

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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

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

the most probable and the seconds 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.

Keywords: Brain-Computer Interface (BCI), Visual-Evoked Potential (VEP), Event-Related Potential (ERP), Cathode Ray Tube (CRT), Liquid-Crystal Display (LCD), timing precision

1. Introduction

In the field of visual neuroscience as well as for Brain-Computer Interfaces (BCIs) [1], 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's 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) [2], is one commonly used method for BCI control [3, 4] 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 variation. Recent studies have shown that latencies of P300 event-related brain potentials (ERP) and error-related potentials (ErrPs) vary depending on the experiment [5, 6] and that correcting latencies leads to a better generalization [6] and an increased performance [7].

As shown by Wilson *et al.* [8] 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 [9] 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 [10]. 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 $0.95/60 = 15.8\overline{3}$ ms between the first and the last pixel of that frame, as shown by Tobias Elze [11]. This property of a monitor, that leads to varying latencies, are attended by some researchers in the field of neuroscience [12], but doesn't 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 [3], steady-state VEPs [4], P300 [13], or ErrPs [14].

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 [15] using the Psychtoolbox-3 [16]. 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 $16.\overline{6}$ milliseconds. 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 [9] 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 $\times$ 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 $16.\overline{6}$ milliseconds.

To avoid fatigue, a run consists of 4 parts with 2 minutes 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 second 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. This 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 [14], in which 24 subjects (18 healthy, 6 motor impaired) used a P300 BCI speller in 2 sessions. For the P300 speller, the BCI2000 implementation was used and the speller was presented on a 19 inch TFT monitor. EEG data was recorded at a sampling rate of 256 Hz with a g.USBamp (g.tec, Austria) EEG amplifier from 16 passive EEG electrodes placed at F3, Fz, F4, T7, C3, Cz, C4, T8, Cp3, Cp4, P3, P4, Po7, Po8, and Oz. More details about the setup can be found in [14].

Processing. EEG data was bandpass filtered by a 4th order Butterworth filter between 0.5 Hz and 12 Hz. To visualize the P300, the average of all non-P300 trials was subtracted from the average of all P300 trials, separately for each session of each subject. This was done for the symbol in the top left of the speller matrix and the symbol in the bottom right. To compute the latency between the two, a cross-correlation analysis was performed.

2.4. Analysis of cVEP BCI data

We used the data of a previous study of us [3] and made an offline analysis to compare the performance differences of correcting the raster latencies versus not correcting.

Setup. The system consisted of an g.USBamp (g.tec, Austria) EEG amplifier, a PC and the CRT monitor (Iiyama A901HT) mentioned above. Stimulus presentation and online classification were operated from the PC. The presentation of the stimuli was synchronized with the EEG amplifier by using the parallel port. The data was recorded using BCI2000 [9] with a sampling rate of 600 Hz. The visual stimuli (black or white) were presented on the monitor with a refresh rate of 60 Hz and a resolution of 640 × 480 pixel. DirectX (Microsoft Inc.) was used to ensure synchronization of the presented stimuli with the refresh rate of the monitor. The presentation layout had 32 targets (8 × 4 grid) surrounded by 28 non-targets and forms a 10 × 6 grid (Fig. 1). For modulation of the stimuli a 63-bit binary m-sequence was used, because of its low autocorrelation property. For each target the same sequence was used for modulation, but circular-shifted by 2 bits for each successive target.

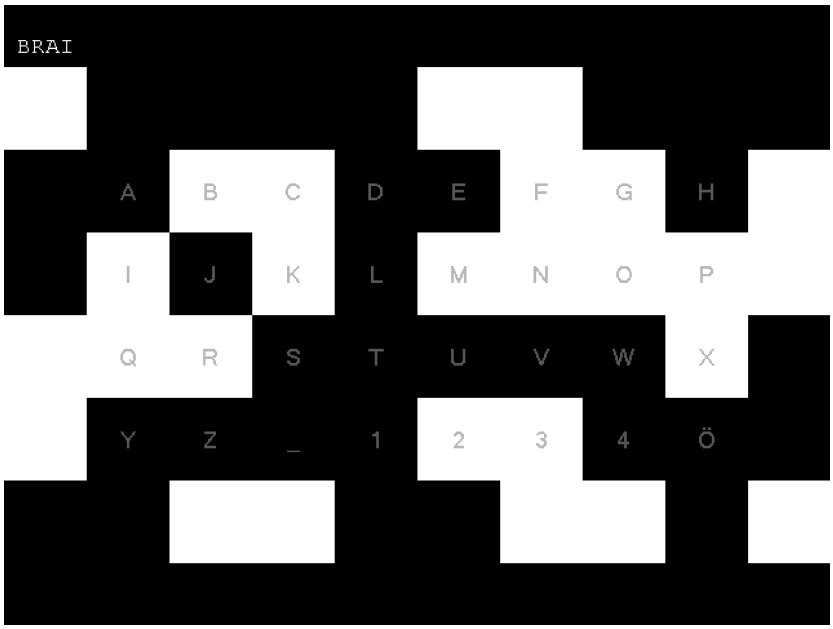

Figure 1: Screenshot of the presentation layer during a trial of the cVEP BCI speller by Spüler *et al.* [3]. The visual stimuli were presented as black or white. The layout has 32 target (8 × 4 grid) surrounded by 28 non-targets and forms a 10 × 6 grid.

Experimental design. Each trial had a length of 1.05 seconds followed by 0.85 seconds for gaze shifting. In total each of the 9 subjects had to perform 64 trials for training and 576 trials for testing, split in two sessions.

Processing. The measured EEG data was processed as described in [17]. In short, the data was spatially filtered by a canonical correlation analysis and rather than averaging the EEG data from multiple stimulation sequences, a one-class support vector machine (OCSVM) was used to estimate the probability distribution of the data. The center of the OCSVM hyper-sphere was used as a template, which was shifted to obtain templates for all targets. By calculating the euclidean distance between a new data point and all templates, the template with the smallest distances to the new data point was obtained and the corresponding target was selected.

To determine the time shift between the top-left and bottom-right position, the cross-correlation was used. As the cVEP BCI has different delays for each stimulus, the data was corrected for the corresponding delay, to only obtain the monitor raster latency.

Correcting raster latencies. As we know the exact position of the middle of each target row, we are able to calculate their exact latency by using the measured raster latency l_m of the used Iiyama A901HT monitor. The latency l_r of each pixel row r of the monitor can be calculated by

$$l_r = r \cdot \frac{l_m}{n}$$

where n is the number of vertical pixels depending on the resolution. In our case $n = 480$ because a resolution of 640×480 was used. Since the data can only be shifted sample-wise, the latencies were converted and rounded to the corresponding number of samples. This allows us to shift the OCSVM templates associated to a target row by the corresponding amount of samples. For the 4 target rows of the presentation layout this results in a shift of 2, 3, 5 and 6 samples, respectively. The corrected templates are used for classification of

the test trials. Of course, the trials used for spatial filter calculation were also corrected by shifting each trial.

Performance evaluation. We used the accuracy of correctly classified targets, or more precisely the difference of the error. As stated before, the distances of the spatially filtered EEG data to all OCSVM templates were calculated, whereby the one with the smallest distance was selected. Additionally to error difference, we analyzed the difference between the most probable template (smallest distance) and the second most probable template for each single trial. An increased difference is expected by correcting the raster latencies, because this indicates a clearer classification.

3. Results

3.1. Measuring raster latencies

First we analyzed the average delay and standard deviation (SD) between the trigger onsets and the real stimulus onsets at the upper left position. For the Iiyama monitor this results in 0.428 ms (SD = 0.0179 ms), for the BenQ monitor in 18.39 ms (SD = 0.034 ms), and for the Dell in 4.26 ms (SD = 0.213 ms). As the standard deviations are quite low, 5 measures are sufficient for each measurement position.

For the bottom right position, the average delay is 15.35 ms (SD = 0.0415 ms) for the Iiyama, 34.26 ms (SD = 0.137 ms) for the BenQ, and 20.14 ms (SD = 0.462 ms) for the Dell. This results in raster latency of 14.92 ms between the upper left and bottom right position for the Iiyama, 15.86 for the BenQ and 15.88 ms for the Dell.

Illustrations of the measures for these monitors are depicted in Fig. 2.

3.2. Effects on SSVEPs

The plots in Fig. 3 show the averaged potential of the 1 second windows of the 1 Hz and 15 Hz stimulation, respectively. The blue lines represent to the

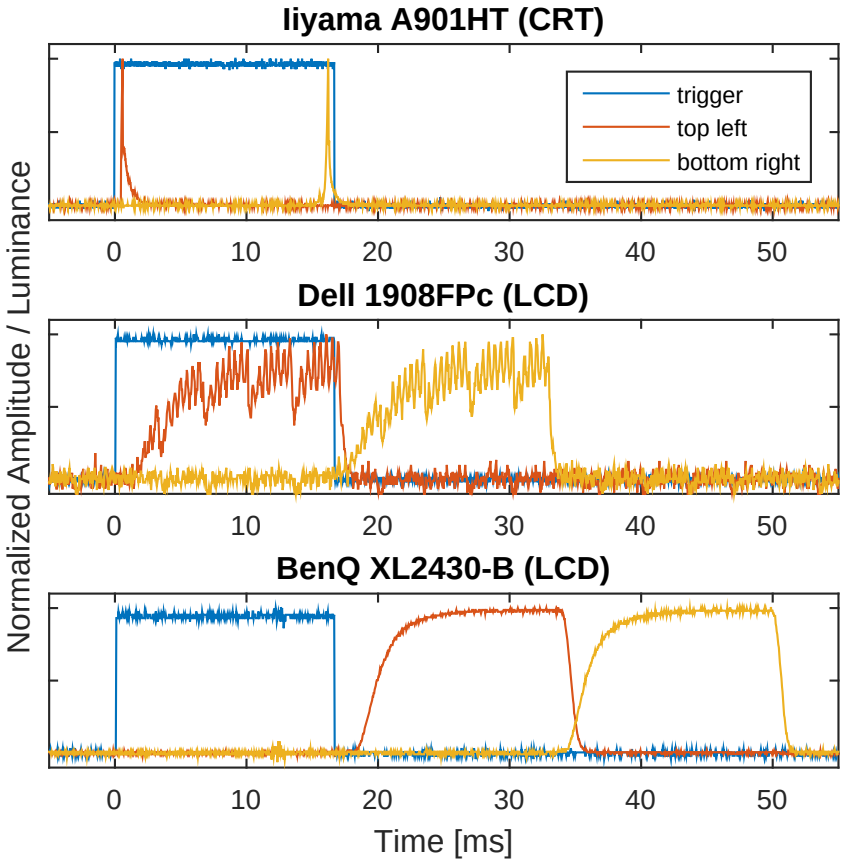

Figure 2: Measured raster latencies of different monitors: Iiyama A901HT, Dell 1908FPc, and BenQ XL2430-B. The blue lines indicate the triggers at which we forced a visual stimulation, for this the parallel port is used. The red and yellow lines are the measured visual stimuli of the monitor at the top left and bottom right position, respectively.

top left position and the red lines the bottom right position. For the cross-correlation analysis of the 1 Hz stimulation we used the first 250 ms of the VEP response, resulting in a shift of 9 samples which corresponds to a time shift of 15 ms. For the 15 Hz stimulation we used the full 1 second window for the cross-correlation analysis, resulting also in 9 samples (15 ms).

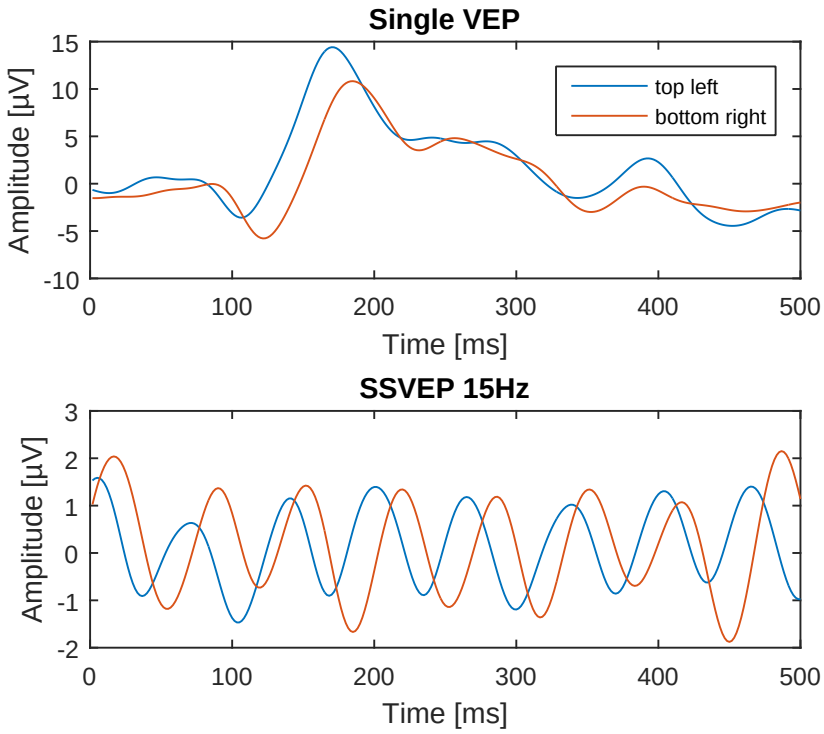

Figure 3: Averaged potential of the EEG data on electrode O2 collected during the SSVEP experiment using stimulation frequencies of 1 Hz (top) and 15 Hz (bottom). The blue lines correspond to the top left position and the red lines to the bottom right. Shown are windows of 500 ms.

3.3. Effects on P300

The plot in Fig. 4 shows the averaged potentials of the P300 EEG data on electrode Cz for the top left and bottom right target, respectively. The cross-correlation analysis revealed a shift of 3 samples which, due to the sampling rate of 256 Hz, corresponds to a time shift of 11.72 ms.

3.4. Effects on cVEP BCI

The previous analysis of the SSVEP data reveals a time shift of the measured VEPs. In order to determine the effects on the classification of a real BCI application, we analyzed the performance difference by taking the raster latencies into account or not.

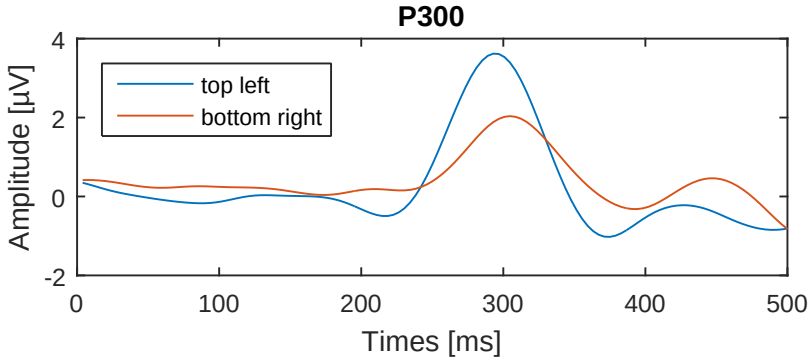

Figure 4: Averaged potential of the P300 EEG data on electrode Cz for the top left and the bottom right symbol in the speller matrix. The blue line corresponds to the top left position and the red line to the bottom right position. Shown are the first 500 ms after trial start.

First, analogous to the SSVEP analysis, Fig. 5 shows the average cVEP response of the top left and bottom right target of subject AD. The cross-correlation analysis of the averaged 1.05 s trials results in 6 samples which corresponds to a time shift of 10 ms.

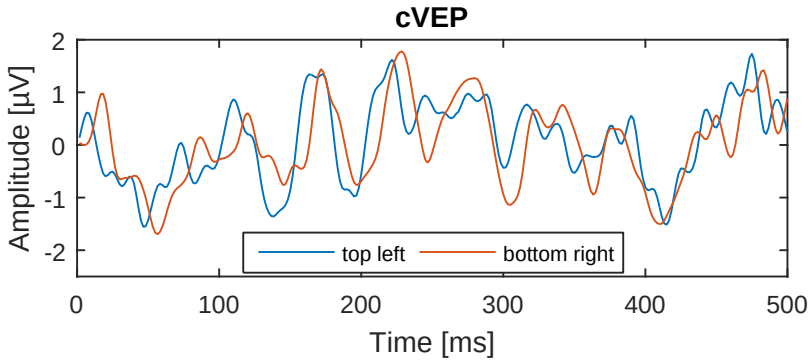

Figure 5: Averaged potential of the spatially filtered EEG data of the first (top left) and last (bottom right) target trials of subject AD. The blue line corresponds to the top left position and the red line to the bottom right position. Data of the bottom right target was corrected for the stimulus delay to only obtain the raster latency. Shown are the first 500 ms after trial start.

Correcting raster latencies. Tab. 1 shows the accuracies for the two sessions (S1 and S2) for each of the 9 subjects. The average accuracy of the not corrected data is 92.02% (7.98% error), whereas the accuracy of the corrected data is 95.39% (4.61% error), which in turn is a significant ($p < 0.05$, paired t-test) error reduction of 42.23%. It is also worth mentioning that correcting the data increased the performance from 60.24% to 89.41% for the subject with the lowest performance (AE S1). Furthermore, the number of perfect runs increased from 1 to 3.

We also analyzed the difference between the euclidean distances of the most probable and second most probable target for all trials of all subjects, whereas only the 9326 correctly classified trials were taken into account. On average the difference is 19.03% for the not corrected data and 22.5% for the corrected data, this is a highly significant ($p < 10^{-5}$, paired t-test) increase of the difference of 18.23%.

Table 1: Comparison of the target prediction accuracies using raster latency correction or not. Data acquisition was split in two sessions (S1 and S2) for nine subjects (AA to AI).

	not corrected		**corrected**	
	S1	S2	S1	S2
AA	96.88%	94.62%	97.22%	97.05%
AB	80.03%	87.48%	87.84%	94.22%
AC	98.61%	98.26%	98.61%	98.26%
AD	98.96%	100.00%	98.96%	100.00%
AE	60.24%	99.31%	89.41%	100.00%
AF	97.74%	94.97%	98.09%	95.66%
AG	99.83%	98.96%	100.00%	99.31%
AH	72.74%	86.63%	78.64%	92.01%
AI	96.18%	94.97%	96.70%	94.97%
Session ∅	89.02%	95.02%	93.94 %	96.83%
Total ∅	92.02%		95.39%	
Error ∅	7.98%		4.61%	

4. Discussion

4.1. Effects of raster latencies

The findings of the raster latency measures appear to be consistent with the results of Tobias Elze [11]. The measured raster latency between the top left and bottom right position of 15.86 ms is nearly 95% of a the refresh-cycle time of $16.\overline{6}$ ms and it seems to be consistent for each refresh cycle and different types of monitors.

We determined a phase shift for SSVEPs between the top left and bottom right position. As we used a 5 cm $\times$ 5 cm square for stimulation, the vertical distance between the top and bottom square is 83.27% of the monitors full display height, therefore, the theoretical time shift should be 13.21 ms. The cross-correlation analysis resulted in 15 ms, but as the time resolution is bound to the sampling rate, the real shift is between $13.\overline{3}$ ms and $16.\overline{6}$ ms.

As expected, the raster latencies also effect ERPs. The analysis of the P300 data revealed a time shift of 11.72 ms (3 samples), but due to the low sampling rate of 256 Hz the real time shift is between 7.81 ms and 15.63 ms. Because of the low sampling rate, an accurate correction of the raster latency was not possible for each target row, therefore, we did not analyze the BCI performance difference. It is known that timings of ERPs also vary across conditions [5, 6], and Mowla *et al.* [7] showed that correcting latencies in general leads to an enhanced performance.

We clearly confirmed that raster latencies have effects on both VEPs and ERPs. We also wanted to prove that this time shift can cause performance differences for BCI applications. As a VEP BCI speller normally arranges targets over several lines of the monitor, the EEG data becomes asynchronous to the stimuli, which in turn reduces the performance. By taking the raster latency into account, we were able to reduce the average target prediction error from 7.98% to 4.61% for all runs of all subjects, this is a reduction of 42.23%. Since the performance by not taking the raster latency into account was already good the room for improvement was quite small. Because of this ceiling effect, sub-

jects with lower initial accuracy will profit more. For example, the accuracy of the subject with lowest performance (AE S1) has improved from 60.24% to 89.41%.

We also analyzed the decision reliability of each target classification. The reliability should be better if the distance difference between the most probable and second most probable target increases. The results reveal a highly significant increase of 18.24%, indicating a generally more reliable classification.

This clearly confirms that correcting the raster latencies is important for cVEP BCIs and will also effect all experiments depending on strict stimulus timing in a millisecond scale using a standard computer monitor for stimulus presentation, like P300, SSVEP, and other VEP experiments.

We also analyzed the average potentials of the spatially filter EEG data of each single subject of the cVEP data and determined an equal shift for all of them (data only shown for one subject), we confirmed that the effect of the raster latency is independent of the subject, at least for VEPs. As stated previously, for ERPs it is known that timings vary in general, but the raster latency causes an additional time shift.

The effects on the performance of a SSVEP BCI depends on the classification method. A method using the frequency domain will result in the same power of frequencies, as the frequency domain is independent of the time shift. Another time shift independent method is the canonical-correlation analysis (CCA) with sine and cosine templates, like the method of Chen *et al.* [4]. For those methods the performance difference by correcting the raster latency should be negligible. On the other side, for classification methods detecting the phase shift [18, 19] or more general which are time dependent, the raster latency correction is highly recommended.

For one-target BCIs [20], the monitor raster latency only causes a static shift from the expected onset to the real onset, which should not affect the performance dramatically.

4.2. Addressing raster latencies

Besides the here used method for correcting the raster latencies for a cVEP BCI by time shifting the templates, one can also use a monitor with a higher refresh rate to reduce the raster latencies. New monitors reach refresh rates up to 240 Hz and quadrupling the refresh rate means the delay between the first and last line is divided by four which is a maximum raster latency of $4.1\overline{6}$ ms.

Alternatively, as a time shift only occurs if the stimuli emitting unit causes raster latencies, one can use other stimuli emitting units, like LEDs [21], indeed this depends on the experiment itself.

Furthermore, one can use classification methods which are not effected by the time shift, like CCA or using only the frequency domain in case of SSVEPs.

5. Conclusion

In this paper, we have presented the effects of the raster latency caused by the image build-up of standard computer monitors on timings of VEPs, P300 and the resultant performance differences of a cVEP BCI.

By using a refresh rate of 60 Hz, the average measured raster latency of the used monitors amounts to 15.55 ms and is reflected in the time shift of the measured SSVEP potentials, which resulted in 15 ms. The results of the offline analysis of the cVEP BCI experiment reveal that the time shift has highly significant effects on the classification performance as the error decreased from 7.98% to 4.61% which is an error reduction of 42.23%.

Interestingly, the raster latencies caused by a monitor are only taken into account by a few neuroscience experiments and not for BCI experiments. Depending on the classification method, the raster latency correction leads to an increased performance for VEP BCIs using a standard computer monitor. But regardless of the method, we recommend to correct the raster latency as it leads to methodical correctness.

References

[1] J. R. Wolpaw, N. Birbaumer, W. J. Heetderks, D. J. McFarland, P. H. Peckham, G. Schalk, E. Donchin, L. A. Quatrano, C. J. Robinson, T. M. Vaughan, Brain-computer interface technology: a review of the first international meeting, IEEE transactions on rehabilitation engineering 8 (2) (2000) 164–173. doi:10.1109/TRE.2000.847807.

[2] E. E. Sutter, The visual evoked response as a communication channel, in: Proceedings of the IEEE Symposium on Biosensors, 1984, pp. 95–100.

[3] M. Spüler, W. Rosenstiel, M. Bogdan, Online adaptation of a c-vep brain-computer interface (bci) based on error-related potentials and unsupervised learning, PloS one 7 (12) (2012) e51077. doi:10.1371/journal.pone.0051077.

[4] X. Chen, Y. Wang, M. Nakanishi, X. Gao, T.-P. Jung, S. Gao, High-speed spelling with a noninvasive brain–computer interface, Proceedings of the national academy of sciences 112 (44) (2015) E6058–E6067. doi:10.1073/pnas.1508080112.

[5] C. J. Gonsalvez, J. Polich, P300 amplitude is determined by target-to-target interval, Psychophysiology 39 (3) (2002) 388–396. doi:10.1017/S0048577201393137.

[6] I. Iturrate, R. Chavarriaga, L. Montesano, J. Minguez, J. Millán, Latency correction of event-related potentials between different experimental protocols, Journal of neural engineering 11 (3) (2014) 036005. doi:10.1088/1741-2560/11/3/036005.

[7] M. R. Mowla, J. E. Huggins, D. E. Thompson, Enhancing p300-bci performance using latency estimation, Brain-Computer Interfaces 4 (3) (2017) 137–145. doi:10.1080/2326263X.2017.1338010.

[8] J. A. Wilson, J. Mellinger, G. Schalk, J. Williams, A procedure for measuring latencies in brain–computer interfaces, IEEE transactions on biomedical engineering 57 (7) (2010) 1785–1797. doi:10.1109/TBME.2010.2047259.

[9] G. Schalk, D. J. McFarland, T. Hinterberger, N. Birbaumer, J. R. Wolpaw, Bci2000: a general-purpose brain-computer interface (bci) system, IEEE Transactions on biomedical engineering 51 (6) (2004) 1034–1043. doi:10.1109/TBME.2004.827072.

[10] I. Pappas, S. Siskos, C. A. Dimitriadis, Active-matrix liquid crystal displays - operation, electronics and analog circuits design, in: G. V. Tkachenko (Ed.), New Developments in Liquid Crystals, InTech, Rijeka, 2009, Ch. 08, pp. 147–170. doi:10.5772/9686.

[11] T. Elze, Achieving precise display timing in visual neuroscience experiments, Journal of neuroscience methods 191 (2) (2010) 171–179. doi:10.1016/j.jneumeth.2010.06.018.

[12] P. Garaizar, M. A. Vadillo, D. López-de Ipiña, H. Matute, Measuring software timing errors in the presentation of visual stimuli in cognitive neuroscience experiments, PloS one 9 (1) (2014) e85108. doi:10.1371/journal.pone.0085108.

[13] R. C. Panicker, S. Puthusserypady, Y. Sun, An asynchronous p300 bci with ssvep-based control state detection, IEEE Transactions on Biomedical Engineering 58 (6) (2011) 1781–1788. doi:10.1109/TBME.2011.2116018.

[14] M. Spüler, M. Bensch, S. Kleih, W. Rosenstiel, M. Bogdan, A. Kübler, Online use of error-related potentials in healthy users and people with severe motor impairment increases performance of a p300-bci, Clinical Neurophysiology 123 (7) (2012) 1328–1337. doi:10.1016/j.clinph.2011.11.082.

[15] MATLAB, version 9.1 (R2016b), The MathWorks Inc., Natick, Massachusetts, 2016.

[16] D. H. Brainard, S. Vision, The psychophysics toolbox, Spatial vision 10 (1997) 433–436.

[17] M. Spüler, A. Walter, W. Rosenstiel, M. Bogdan, Spatial filtering based on canonical correlation analysis for classification of evoked or event-related potentials in eeg data, IEEE Transactions on Neural Systems and Rehabilitation Engineering 22 (6) (2014) 1097–1103. doi:10.1109/TNSRE.2013.2290870.

[18] C.-L. Yeh, P.-L. Lee, W.-M. Chen, C.-Y. Chang, Y.-T. Wu, G.-Y. Lan, Improvement of classification accuracy in a phase-tagged steady-state visual evoked potential-based brain computer interface using multiclass support vector machine, Biomedical engineering online 12 (1) (2013) 46. doi:10.1186/1475-925X-12-46.

[19] J. Pan, X. Gao, F. Duan, Z. Yan, S. Gao, Enhancing the classification accuracy of steady-state visual evoked potential-based brain–computer interfaces using phase constrained canonical correlation analysis, Journal of neural engineering 8 (3) (2011) 036027. doi:10.1088/1741-2560/8/3/036027.

[20] J. Jin, I. Daly, Y. Zhang, X. Wang, A. Cichocki, An optimized erp brain–computer interface based on facial expression changes, Journal of neural engineering 11 (3) (2014) 036004. doi:10.1088/1741-2560/11/3/036004.

[21] H.-J. Hwang, J.-H. Lim, Y.-J. Jung, H. Choi, S. W. Lee, C.-H. Im, Development of an ssvep-based bci spelling system adopting a qwerty-style led keyboard, Journal of neuroscience methods 208 (1) (2012) 59–65.