We investigate the feasibility of combining off-the-shelf virtual reality headsets and electroencephalography. EEG is a highly sensitive tool and subject to strong distortions when exerting physical force like mounting a VR headset on top of it that twists sensors and cables. Our study compares the signal quality of EEG in VR against immersive dome environments and traditional displays using an oddball paradigm experimental design. Furthermore, we compare the signal quality of EEG when combined with a commodity VR headset without modification against a modified version that reduces physical strain on the EEG headset. Our results indicate, that it is possible to combine EEG and VR even without modification under certain conditions. VR headset customisation improves signal quality results. Additionally, display latency of the different modalities is visible on a neurological level.

Index Terms: Human-centered computing—Visualization—Visualization techniques—Tree maps: Human-centered computing—Visualization—Visualization design and evaluation methods

1 INTRODUCTION

Psycho-physiological or functional neuro-imaging measurements sensing brain waves like electroencephalography (EEG) are powerful techniques for measuring brain activity while interacting with virtual reality (VR) environments. Immersion and the feeling of presence is higher in VR than with traditional presentation methods like a computer screen [2]. The increased extend of this immersion may be measured objectively by using implicit measures like EEG. However, using these methods in conjunction with virtual reality devices can introduce problems due to physical and technical constraints. EEG uses multiple channels to measure brain activity with a combination of cables and sensors that are attached to a head cap. This setup may interfere with wearing a head-mounted display (headset) in a VR environment and imposes a challenge to fuse both the EEG cap and the VR headset. When a subject wears the EEG cap, the VR headset must be worn over the cap and the arrangement of cables and sensors attached to the cap interferes with the positioning of the VR headset. The VR headset straps are made of a combination of flexible rubber and non-flexible garment that exerts pressure on the sensors displacing the sensors and twisting the cables, in turn resulting in poor data quality. Especially in real-world applications where people move and look around this becomes a major problem.

In this study, we evaluate the signal quality of EEG measurement when wearing an EEG cap and a VR headset at the same time. For this purpose, we design a very simple experiment following the oddball paradigm that can be run on three different presentation modalities: a VR head-mounted display (VR), an immersive full-dome environment (dome) and a traditional display setup (screen).

For comparison, we conduct the same experiment without a VR headset in an immersive full-dome environment (dome) [5] and a classical display setup (screen). The dome is an immersive real-time hemispherical video projection system with a diameter of 5m and is tilted backward by 20° and the rear side almost touches the floor while the front side reaches a height of around 1.9 m. The dome delivers a similar experience to a VR headset without the additional equipment that needs to be strapped to an observer’s head [5]. We conduct our oddball experiment on all three presentation modalities in three different conditions: without head motion, with horizontal and vertical head motion. Both the VR and dome modality allow for larger (head-) motion within the environment than a traditional screen setup.

We employ the event related potential technique [13] that analyses EEG data in the time domain in response to specific sensory or cognitive events. We chose this method as a very common and straight-forward approach as results can be intuitively interpreted compared to other methods that employ frequency domain analyses that are also used within EEG research.

Our results suggest, that it is possible to combine EEG and VR even without modification under certain conditions.

2 RELATED WORK

2.1 EEG and screen-based VR

Virtual reality has been investigated in a number of studies in screen-based environments. Neural correlates of spatial presence in screen-based VR using EEG and peripheral physiological signals are increased activity in parietal and occipital areas of the brain and in autonomic somatic reactions together with decreased activity in frontal structures [1]. Presence has also been measured from EEG using event related potentials in a cave like environment during passive and active cycling [21]. Emotions in VR presented on a large back-projected screen have been investigated using a consumer-grade EEG headset [17]. Here, participants navigated through a virtual environment that was atmospherically manipulated using affective music and pictures. In our present work, we also conduct our experiment within a screen-based environment, specifically an immersive full-dome environment [5].

2.2 EEG and headset-based VR

A number of studies that use EEG in conjunction with VR headsets have been conducted. These have the added difficulty of combining the VR headset montage with the EEG cap without introducing signal distortions due to physical pressure to the electrodes. Headset-based virtual reality induced emotion has been assessed with occip-
ital alpha power [10]. The HTC Vive was mounted on top of the EEG headset with the participants instructed not to move to avoid signal disturbances. Another study that placed the headset strap over the EEG headset looked into meditation applications by an interplay of the alpha and theta wave band [11]. They found that their live neuro-feedback increased the level of presence within the virtual environment. A demo using two different headsets in conjunction with a single electrode EEG headset and a physiology wrist-worn device was conducted for quality of experience assessment with no evaluation [18]. By using only a single electrode, the EEG measurement did not interfere with the headset montage. Physiological signals only, avoiding the EEG montage problem, have been used in a study that compares emotions evoked in headset and screen-based VR setups [6]. A consumer-grade EEG headset was used simultaneously with the HTC Vive to assess emotions in VR with frequency band powers [7]. The participants were instructed to hold the headset with their hands as the headset did not fit with the device. Similarly, the same EEG headset was combined with an Oculus Rift, with the EEG headset mounted below the HMD [14]. A wireless 9-electrode EEG headset has been combined with a Samsung Gear VR for emotion classification [15]. All these studies have in common that participants do not move. Emotions in VR have also been measured using near-infrared spectroscopy (fNIRS) that exposes the same montage problems as EEG devices [19]. Here, a custom-built VR helmet has been proposed to properly place the measurement probes. The challenges in simultaneously recording EEG or fNIRS with HMDs have been addressed with the proposition of a new head-cap that is compatible with specific HMDs [9].

3 EXPERIMENT

We investigate the signal quality of EEG when combined with a VR head-mounted display (VR) in comparison to an immersive full-dome environment (dome) and a traditional computer display setup (screen). This section explains the experimental design.

3.1 VR Headset

The experiment with the VR display modality has been conducted twice. The first run featured an off-the-shelf HTC Vive headset without any modifications with the EEG cap worn below the headset strap that holds the Vive in place on the participant’s head. The headset straps are made of a combination of flexible rubber and non-flexible garment that exerts pressure on the sensors displacing the probes and twisting the cables, which also may impact data quality. As the strap exerts physical force on the EEG cap, the participants for this modality complained about discomfort and pain due to the pressure on the electrodes under the strap after a short period of time. We mitigate these issues by introducing a custom-modification of the VR headset strap adapted for research with virtual reality system (Figure 1). Parts of the strap have been extended with flexible material to provide more space for fitting the EEG cap. Cut-outs were added to the strap at the EEG sensor positions to remove the pressure. The elliptical cut-outs allow for slightly differing sensor positions to support different head sizes. The EEG cap battery and wireless transmission module is usually fastened with velcro pads. The modified VR strap has a velcro pad in the same position to hold the module in place. The second run was conducted using the modified VR headset strap (VR-mod).

3.2 Design

We conducted a traditional oddball paradigm experiment on all three display modalities: VR, dome and screen. The oddball paradigm is an experimental design used within psychology research where presentations of repetitive stimuli are infrequently interrupted by a deviant stimulus [20]. The VR modality was conducted with and without headset strap modification. The experiments did not differ in look-and-feel or user experience as our custom-designed rendering...
framework runs the same experiment without modifications across all devices. The basic common properties of all our experiments include a fixation cross and a sphere object (ball) in front of a black background. The fixation cross is displayed for the entire duration of an experiment run and is replaced by the ball either in green or red colour. The ball appears repetitively every 2-3 seconds (randomised) either green (80% of the time) or red (20% of the time) for a duration of 0.5 s. The red ball serves as target or deviant stimulus from the green ball that is the base or control stimulus. After the ball vanishes, the cross is immediately shown again to let neural activity return to a baseline. The ball stimulus was shown for 200 trials (160 times green ball and 40 times red ball) to every participant. The cross and the ball are either shown directly in front of the observer without any motion or move around the observer’s head on a circle arc at certain eccentricities. The roundtrip time for the moving ball to return to its initial position is 5 s. The speed at which both objects float around the observer’s head follows simple harmonic motion dynamics to allow for natural head movement. For every display modality (VR, dome, screen), we tested three motion conditions:

**Static** with the fixation cross not moving as in the most basic oddball variant. We instruct the participant not to move and reduce conscious muscular activity.

**Horizontally** with the cross moving horizontally on a half circle around the participant. The participants are instructed to move their heads according to the cross motion. Horizontal motion eccentricity for the screen is 27° to both sides for the observer’s view and 81° for the VR and dome modality. Eccentricity for the screen is smaller because the stimulus must not leave the visible display area.

**Vertically** with the cross moving vertically on a circle arc around the participant. Vertical motion eccentricity for the screen is 18° to both sides, 54° for the dome modality and 81° for the VR modality. Again, the screen has the least display estate, so motion eccentricity is smaller. The dome also has a diminished eccentricity for vertical motion since its tilted hemispherical hardware design limits the visible projection area towards the floor [5].

We call these motion conditions static, horizontal and vertical respectively, with the latter two inducing head motion. The moving cases are the interesting ones, as they may induce the most artefacts during measurement.

3.3 Participants
The experiment performed in total by 20 participants (14 female, 6 male, aged 19–34, mean: 22.43, sd: 4.79) with normal or corrected to normal vision, no report of eye or neurological impairment, e.g. deuteranomaly (red-green colour-blindness) (between subjects design). Each display modality (VR, VR-mod, dome, screen) was assessed by 5 participants. We also assessed our participants for their current general feeling of well-being. The participants were asked to fill out the simulator sickness questionnaire (SSQ) twice, before and after the experiment session [8]. Motion sickness may become a real problem for some people when enter a virtual world. Conflicting sensory inputs may cause discomfort, specifically, sensations like dizziness, nausea, headaches, sweating, excessive or salivating may occur.

Our experiment is set in a very simple scenery: a completely dark environment with just the cross or the ball in its centre. There is no locomotion required and physical head movements are resembled in VR.

3.4 Setup, Acquisition and Processing
The experiment for screen modality was presented on a 47-inch screen (100 Hz, 1920 x 1080 px) at a distance of approximately 90 cm from the participants. EEG signals were collected using a g.tec g.Gamma cap2 with 16 active electrodes sampled at 250 Hz. The ground electrode is located at the fronto-central area and the reference on the right ear. The Cz electrode was used for later re-reference.

The EEG signal was high-pass drift-filtered at 0.1 Hz and notch-filtered around 50 Hz with a zero-phase filter to remove power line noise. The EEG data was baseline corrected using the 300 ms interval before the stimulus onset. We filtered the trials for eye blinks and removed remaining muscle or movement artefacts by manual inspection. For analysis, we used the MNE toolbox [4].

The recording sessions included a written informed consent, introduction to the experiment, setup of the EEG system, fitting of the VR headset and the actual experiment.

We use the event related potential (ERP) technique for analysing the EEG data [13]. The Oz electrode was chosen for ERP visualisation as it covers the earliest cortical visual processing area [12]. The neural responses are called event-related potentials because they are embedded within the EEG as electric potentials associated to specific events [13]. The continuous time-series data collected from the EEG system was segmented into epochs of 1000 ms duration relative to the onset of the presented stimulus. The data was baseline corrected using the 300 ms interval before the stimulus onset to account for individual power levels of the participants.

According to the ERP technique, our data then has been condition-wise grand-averaged over all participants and all electrodes for a given experiment run to remove noise, i.e. the trials for the stimuli of the same ball colour and the same display modality of the participants have been averaged.

3.5 Analysis
We hypothesise the VR modality to introduce more noise and distortions on the EEG signal than the dome and screen modality. The screen modality is expected to introduce the least noise for motion conditions. Stimulus motion eccentricity is smallest for this modality (27° horizontal, 18° vertical) because the size limitations of a conventional rectangular display. This reduces the induced head motion of the participants.

For the VR modality, two experiment runs were conducted: without and with modified headset strap. We further expect the modified VR modality (VR-mod) to introduce less distortions than the unmodified version. The modification removes the pressure from the measurement electrodes resulting in fewer twists of the sensors and cables. We present qualitative results of certain associated brain
While our focus of this work is the general applicability of EEG
This section presents the results of the EEG data analysis (see 3.5).

Table 1: Mean values ($\mu V$) of the bootstrapped 95% confidence intervals for the Oz sensor.

<table>
<thead>
<tr>
<th></th>
<th>Static</th>
<th>Horizontal</th>
<th>Vertical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screen</td>
<td>3.47</td>
<td>4.03</td>
<td>3.51</td>
</tr>
<tr>
<td>Dome</td>
<td>3.67</td>
<td>6.25</td>
<td>5.26</td>
</tr>
<tr>
<td>VR</td>
<td>4.49</td>
<td>7.22</td>
<td>85.11</td>
</tr>
<tr>
<td>VR mod</td>
<td>3.52</td>
<td>4.57</td>
<td>26.28</td>
</tr>
</tbody>
</table>

Table 2: Peak onsets times for P2 ERP component in seconds. Display latency difference between screen / dome and VR of ca 0.05 s is clearly visible in the neural response. VR vertical did not show an ERP.

<table>
<thead>
<tr>
<th></th>
<th>Static</th>
<th>Horizontal</th>
<th>Vertical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screen</td>
<td>0.196</td>
<td>0.200</td>
<td>0.208s</td>
</tr>
<tr>
<td>Dome</td>
<td>0.188</td>
<td>0.208</td>
<td>0.216</td>
</tr>
<tr>
<td>VR</td>
<td>0.140</td>
<td>0.136</td>
<td>–</td>
</tr>
<tr>
<td>VR mod</td>
<td>0.140</td>
<td>0.168</td>
<td>0.156s</td>
</tr>
</tbody>
</table>

areas for an initial intuition followed by measuring increases in the between-trial variability for all modalities and conditions with confidence intervals.

4 RESULTS

This section presents the results of the EEG data analysis (see 3.5).
While our focus of this work is the general applicability of EEG together with VR, we present our results from the viewpoint of the evaluation of the visual oddball experiment. Visual reactions first occur in the primary visual cortex located at the occipital brain area at the back of the head (Brodmann area 17).

Table 1 shows

For visualisation purposes, we show plots of the Oz electrode that is located at this area. Figure 3 shows an event-related potential (ERP) plot for a qualitative intuition for the data quality. The plots show the grand-averages of the EEG signal at the time of the stimulus onset, that is the appearance of the ball, denoted by time-point zero. The shaded area around the mean shows the bootstrapped 95% confidence interval. Expected neural responses for our experiment over the primary visual cortex are visible around 0.2 s (called the P2 component, which is a positive deflection around 0.2 s after a stimulus onset) in the signal that has been studied in the context of visual priming and oddball paradigms [16].

Generally, the P2 component is hypothesised to be part of a cognitive matching system that compares sensory inputs with stored memory [3, 13]. Especially in oddball paradigm experiments, one is usually interested in differing amplitude peaks or onsets around this component where the amplitude is enhanced for targets. In contrast to this specific focus, in our experiment, our main focus is on the signal quality of the EEG rather than the outcome of the experiment itself. We use the confidence interval around the mean as an indicator of signal deviation between the participants and trials for each screen modality and motion condition. Movements in general as well as pressure on the EEG sensors introduce signal distortions that must be kept to a minimum for reliable measurements. We also employ the number of trials that were rejected due to signal distortions as a quality measure. Another measure for signal quality are usable sensors.

We start with the results of the experiment conducted with the conventional computer display modality (screen).

4.1 Screen

This is the traditional setup with stimulus presentation on a conventional computer display. Here, the participants wear only the EEG cap without any distortions that may be introduced by wearing a VR headset. Also, for the moving conditions, head motion eccentricity is smallest since the ball rotating around the participants head needs to stay visible on screen. Therefore, signal distortion due to movement are minimised for the motion conditions. This is the most simple variant of our experiment and serves as control since it features the traditional EEG lab research setup with the participant sitting in front of a presentation screen without any motion. Figure 3 shows the ERP plot for the Oz electrode. A pronounced neural reaction is visible around 0.2 s (P2 component) in response to the appearance of the ball stimulus. There is also a second peak visible around 0.7 s that is accounted to the return to the fixation cross that appears after the ball has been shown for 0.3 s. For the oddball experiment, different P2 component amplitudes are expected for the standard and deviant stimulus (green and red ball).

 traditionally measured increases in the error of the EEG.

4.2 Dome

The dome modality is similar to the screen in terms of headset comfort as the participants only wear the EEG cap here. Larger stimulus eccentricities are allowed due to the hardware shape of the dome which may in turn introduce larger distortions in the EEG signal due to larger sensor and cable twist. We choose these values, such that the stimulus always remains visible on the increased screen estate in the dome and allow for larger natural head movement [5]. Qualitatively (Figure 3) and quantitatively (Table 1), the EEG signal quality diminishes compared to the screen modality. Due to the larger possible head motions than for the screen, the confidence interval increases especially for vertical motion. This is due to the even larger eccentricity difference between screen and dome for the vertical condition. The problem with the battery pack also applies here. On pronounced vertical motion, the battery pack may get pressure from the neck of the observer. Again, the red ball has significantly fewer repetitions, increasing the error of the EEG even more here due to the larger motion eccentricity. The percentage of rejected trials due to signal artefacts of around 12% remains stable across the motion conditions. Like for the screen modality, frontal sensors exhibited the most problems in general mainly due to eye blink artefacts.

4.3 VR

This is the most challenging display modality as the VR headset is mounted on top of the EEG cap. Signal distortions are introduced...
Figure 3: Plots for the electrode Oz covering the primary visual cortex at the occipital site for all display modalities and motion conditions. Experiment conditions without head motion (static) show the qualitatively clearest plots. The physical delay of the display modalities is visible in the neural response with the VR headset being 50 ms faster than dome and screen.
by pressure and twist of the sensors and cables, especially during the motion conditions. Most participants complain about discomfort and even pain when wearing the unmodified VR headset above the EEG cap. The confidence intervals are larger for the unmodified VR headset than compared to screen and dome, especially for the vertical motion where the error indicates no usable signal. Trial rejection rates for the unmodified condition are 29%, 9% and 39% for the static, horizontal and vertical conditions. Interestingly, the rejection rate for the horizontal motion condition is comparably low, similar to the lower error rate. A possible explanation is orally reported decreased discomfort level when participants move their heads as compared to hold it still which in turn introduced fewer involuntary muscle artefacts. Despite the large rejection rate for the vertical condition, no clear signal is visible. Also the error rate indicates severe problems rendering the unmodified VR headset unusable for this condition. In contrast to the modalities without a VR headset, here, the most problematic electrodes are at occipital sites. Here, the headset strap and the battery pack interfere. Especially for motion, the strap introduces undesired tear to the battery and conversely to the underlying EEG cap in this area. Also, head motion is highest for this modality and covers the largest range to account for the freedom of looking around in VR.

Note, that the P2 component peaks around 0.05 s earlier for the VR modality, than for screen or dome. This is in line with the end-to-end pipeline timing results of the dome [5] and screen latency. This latency is visible within the neural response and suggests EEG to be a suitable measure for perceptual display latency.

4.4 Modified VR
The second experiment run features the redesign of the VR strap. Participants do not report any discomfort for this modality. Here, the battery pack is mounted above the headset strap part, that now covers the back of the head (Figure 1b). Especially for motion, the battery is prone to introduce undesired tear to the strap and conversely to the underlying EEG cap in this area. The confidence interval for the static condition drops to a level comparable to the screen modality but is increased for the motion conditions. The confidence interval for the horizontal motion condition is higher than for the unmodified headset. Qualitatively, the P2 component is still visible for the motion conditions but does not meet the expectations of a clean ERP plot.

Trial rejection rates for the modified VR condition drop to 8%, 17% and 15% for the static, horizontal and vertical conditions. Also, the display latency timing is visible here as shown previously.

5 Discussion and Conclusion
We have established a baseline for what is possible when combining EEG and a VR headset. Our results indicate that this combination is feasible but requires more research in terms of properly mounting the VR headset above the EEG cap. We find an improvement in signal quality with the custom modification of our VR headset strap. More trials become usable and confidence intervals become narrower when head motion is absent. For the motion conditions, the modified VR headset only improved for vertical movements but not horizontal movements. This could be accounted to undesired additional motion induced by the battery pack that is attached to the VR strap. To reduce impact caused by the battery pack, future designs should consider placing it not directly at the head, i.e. to the participants belt. Also, more repetitions with more participants reduce general noise. The EEG cap is shipped in a single size, so differences in participants’ head sizes also account for the proper fit. Another weakness that is amplified by the EEG cap is the placement of the ground sensor that sits below the central VR strap element. If this sensor is misplaced by tear on the strap, then noise increases in all electrodes or the signal becomes completely unusable.

In the future, we suggest to run this experiment with more participants to reduce noise. It would also be interesting to design an experiment that uses frequency analysis. Harware-wise, a more direct integration of the EEG cap and the VR headset possibly with the help of both vendors would significantly increase data quality.

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