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Comparing the Neuro-Physiological Effects of Cinematic Virtual Reality with 2D Monitors

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Figure 1: Cinematic Virtual Reality creates an immersive viewing experience where the audience can “watch films” inside “films”.

Abstract

In this work, we explore if the immersion afforded by Virtual Reality can improve the cognitive integration of information in Cinematic Virtual Reality (CVR). We conducted a user study examining participants’ cognitive activities (recall performance and cortical response) when consuming visual information of emotional and emotionally neutral scenes in a non-CVR environment (i.e. a monitor) versus a CVR environment (i.e. a head-mounted display). Cortical response was recorded using electroencephalography. The results showed that participants had greater early visual attention with neutral emotions in a CVR environment, and showed higher overall alpha power in a CVR environment. The use of CVR did not significantly affect participants’ recall performance.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality; Human-centered computing—Visualization

1 Introduction

We are living in an era where the advancement of technologies continues to provide new vehicles for communicating messages. Cinematic Virtual Reality (CVR) is an emerging technique for presenting visuals that is gaining prominence [38]. CVR (Figure 1) is the application of Virtual Reality (VR) to the film industry. CVR aims for immersive viewing experiences where the audience can look, and potentially move, inside a “film” in synthetic VR worlds with spatialized audio [41, 43, 54]. It has been shown that VR enhances procedural and declarative learning by providing a simulated immersive environment [42, 52]. In these cases, the immersive and life-like simulated environment and interactions can better engage a viewer compared to other non-immersive mediums and consequently improve their understanding of the learning materials. Given the power of VR, we are motivated to investigate whether CVR, by way of the affordances of VR, has the potential to improve the effectiveness of the presentation of visual information when compared to non-CVR media.

In this work, we generated visual information of 3D animated scenes and compared viewing them using a traditional 2D monitor to viewing them in CVR environment (i.e. a head-mounted display (HMD)). Two fundamental factors—recall and early visual attention—were targeted. Recall measures the level that viewers of the visual information presentation can bring the information back to their mind. Early visual attention is part of the early visual processing of human brain, the level of which reflects the ability of human brain to mediate the selection of relevant and the filtering out of irrelevant information at the early stage of being presented with visual information. Both factors are important for visual information presentation. As previous studies have shown the influence of emotions on attention [37] and memory encoding [12], we measured and compared recall and visual attention across three types of emotions: negative, neutral, and positive. Signal Detection Theory (SDT; [1]) was applied to assess participants’ recall performance, while electroencephalography (EEG) was used to measure early visual attention. The use of EEG allowed us to perform a detailed and accurate interpretation of participants’ attention responses to stimuli on a neurophysiological level [4, 51]. In addition, alpha activity has been well presented to relate to human cognition [4, 51]. In this work, we also measured participants’ alpha activity for early exploration.

The contribution of this work is as follows: firstly, our work shows the neuro-physiological effects of CVR and reveals the benefits of using CVR techniques for the consumption and comprehension of visual information provided by 3D computer-generated content. Specifically, we found: 1) 3D computer-generated content in CVR environment was associated with higher early visual attention for scenes evoking neutral emotions that was not observed in scenes

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evoking positive and negative emotions; and 2) applying CVR techniques for displaying 3D computer-generated content elicits higher overall alpha power, which likely indicates a lower mental effort and/or an active inhibition. Furthermore, as this work represents an initial exploration of the neurophysiological evaluation of CVR techniques, we also present the issues faced when running such a study and hope to reveal potential future direction for this area of research.

The remainder of the paper is structured as follows: after the review of the relevant background literature, we describe our experiment in detail, including the design, progress, and results. We will also present our discussion of the insights from our experiment and data analysis. We then present limitations, conclusion, and the future direction of this work.

2 Background

In this section, we will introduce the state of current CVR research and problems that motivated our work. Then, we will introduce the background knowledge of our neurophysiological measurements. The experiment involved inducing different moods and emotions in immersive virtual environment. We will also briefly introduce current research for arousing emotions in this section.

2.1 Cinematic Virtual Reality

The affordances of VR differentiate CVR from traditional cinematic media in a number of ways; the visual stereo effect, the free control of point of view, and the encompassing field of view are all factors that must be considered when developing CVR media. Consequently, CVR requires different methods for development and evaluation compared to traditional 2D displays [38,41]. Chang [18] explored applying some of the techniques from traditional film making (e.g. number of shots and cuts, shot size variation, and angle variation) to CVR. Mateer [41] presented a number of potential methods for directing viewers' attention in CVR applications, including visual differentiation of elements (e.g. differences in color and shape). Nielsen et al. [43] presented and compared two types of attention cues in CVR applications: *firefly* (i.e. a small flying firefly to guide viewers attention) and *forced rotation* (i.e. disabling viewers' control of rotation and forcing them to face to the right direction). Results from this research indicated that *firefly* was generally perceived as a better guide. Kjær et al. [31] explored multiple shots in CVR by studying the effects of different cut frequency and concluded that the cut frequency did not affect viewers' watching experience. Most recently, Cao et al. [16] studied different transition effects in CVR applications, namely cut, fade, and a VR portal (i.e. a virtual doorway that connects two shots). These aforementioned studies primarily relied on subjective questionnaire measures that may be sensitive to participants' accuracy of self-description, while the measured metrics are not always easy to describe for participants. The development and evaluation of more measurements are necessary.

2.2 Recall in Cinematic Virtual Reality

The effect of CVR on memory is not well understood; there are only three related studies [26,38,50], and no accordant results that can present a particular conclusion. Rizzo et al. [50] investigated people's memory performance by comparing watching panoramic videos on different media including a HMD and a standard television. They suspected that the level of engagement would be increased in HMD (referred to as the Panoramic condition in their study) which would result in an increase of long term recall. However, their results showed worse free recall and recognition in the HMD group. Their explanation for this focused on the extra mental effort brought by the additional information (in Panoramic conditions). However, MacQuarrie and Steed [38] could not replicate these results, instead finding that CVR brought no significant difference to viewers' memory. They suspected it might be because of their sample size; as MacQuarrie and Steed state, "memory is highly variable between individuals, however, and therefore more than 63 participants [21 participants in each condition] may be required to produce a statistically significant result". He et al. [26] recently conducted a third experiment comparing viewers' recall performance after they watched a drama in VR and on a standard television. They found that participants were better at remembering events with strong visual or audio effects when they are in VR. This study revealed a fact that the effect of CVR on viewers' recall could be affected by other factors including (but not limited to) visual and audio effects, which should be considered in future research.

Recall is normally measured by the accuracy rate of participants' description of the items in question (e.g. *free recall* [34] and *cued recall* [8]) or the answers to testing questions [2] (e.g. *how many items have you seen?*). However, they do not measure the sensitivity for distinguishing stimuli and fillers. Furthermore, we believe the results of testing participants' recall of visual stimuli based on textual or verbal responses could also be influenced by other issues such as participants' linguistic ability. One well-understood method to address these issues comes from applying SDT [1]. SDT indexes viewers' behavioral responses by a d' score. d' is calculated by the difference in z-scores between two response values: *Hits* and *False Alarms(FA)*. *Hit* refer to a Yes response given to old information (facts that were seen before); *FA* refers to a Yes response to new information (facts that were not seen before).

2.3 Neurophysiological Measurements

EEG measures the electrical cortical response of the brain, of which the wearer may not be consciously aware, and provide high temporal resolution of information processing [4,51]. It is well established that EEG data can reflect important aspects of the cognitive process, including attention processing [57] and mental effort [4]. There have been a number of studies utilizing EEG for the measurements in VR [9,24,32,35,36]. However, these studies have generally focused on task-based activities in VR, whereas CVR experiences are primarily passive and are not task based. A few studies have explored the use of EEG in CVR environment [26,33] that demonstrated the possibility of using EEG to understand the passive watching experience in CVR applications. For example, He et al. [26] applied EEG to measure and compare viewers' engagement levels when they watched a drama in VR and on a 2D screen. They found that people in VR were more engaged than the 2D screen. Based on these previous works, we applied EEG to examine the effects of CVR at the neurophysiological level. Event-related potential (ERP) was adopted to reflect early visual attention and alpha power was selected for the further exploration of human cognition in CVR.

2.3.1 ERP

ERPs are defined as "small phasic brain potentials that are time-locked to the occurrence of concrete events" [57]. In other words, ERPs illustrate the brain responses that are the direct results of specific stimulus. ERP studies have shown that early ERP components are able to reflect the magnitude of attentional processes of stimuli [13]. Specifically, attended stimuli, relative to unattended stimuli, could induce enhanced ERP components (maximal over posterior scalp), providing direct evidence of a higher level of attentional processing [22,27]. In our work, we looked into two parietal components where the attentional effect is consistently found: C1 and N1. C1 normally peaks around 80ms after the onset of stimuli and is argued to reflect low-level visual characteristics [45]; and N1 peaks between 160ms to 210ms [58].

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2.3.2 Alpha Power

The continuous EEG signal is composed of various frequency bands, such as alpha, theta, beta, delta, and gamma. Among these bands, alpha activity (centered around 10 Hz within a range of approximately 8-13 Hz) was the first EEG signal that was discovered to relate to human cognition [11]; however, related research and findings diverge in terms of interpretation. For many years, the dominant interpretation of alpha activity is that it reflects the activating level of cortical brain regions, which also refers to a term "mental effort" [20, 30]. Specifically, a lower alpha power (defined as "total energy intensity of an electrode on a certain region at alpha bands" [21]) is associated with sensory stimulation or increased mental activity [28, 53]. Some other research suggests that an increased alpha power is associated with a mechanism of inhibition—a mechanism to reduce the processing of interfering information for current tasks by reducing neural excitability—while the decreases of alpha power indicate the release from inhibition [29, 51].

2.4 Mood Induction in Virtual Environment

The emotions' effect on people's recall and attention activities has long been explored [3, 14, 44, 47]. A well-agreed notion is that emotional elements are associated with enhanced attention and memory encoding activities as compared to non-emotional elements [48]. Virtual Environments (VE) has been presented to provide the unique possibility of creating rich and life-like replications of emotional stimuli and enhance emotion induction as compared to non-VE [23]. Therefore, it is reasonable to argue that the effect of emotions on recall and attention would be stronger in VEs as compared to non-VEs. However, there is no evidence that can prove this hypothesis.

There has been limited research exploring VE for arousing emotions [6, 7, 23]. One relevant area of research is Mood Induction Procedures (MIP) [40]. Before moving on to a introduction of VE for MIP, it is necessary to conceptually distinguish the terms emotion and mood. In a great number of MIP studies, the terms emotions and mood are used interchangeably [15, 55], while some researchers argue that there are distinct characteristics between the two terms. For example, Beedie et al. [10] concluded that emotions are "less controllable" and "more intense, brief, volatile, etc." as compared to mood after conducting an interview with both non-academic and academic individuals. In addition, emotions are thought to be caused by specific cues while moods are not. In our work, we adopt the same speculation from Felnhofer et al. [23]: we use "mood" to describe the emotional tones of VE and use "emotion" when discussing individuals' emotional states which are targeted by MIPs.

In current research regarding the use of VE for MIP, "a virtual park" is the most popular setting [6, 49]. One of the reasons according to Baños et al. [6] is that a virtual park includes various elements (e.g. water, sky, trees), allowing the parameters of which (e.g. lighting, brightness, color) to be easily modified for inducing different mood. Common mood induction methods include the control of sounds, music, lighting effects, environmental elements, and so forth. For example, Baños et al. [6] induced sadness in users by making: "The park is grey, it is a cloudy day, the trees have no leaves, there are no people in the park and music that is heard is very sad".

3 Experiment

We designed and conducted a within-participants experiment comparing 3D computer-generated animations played in CVR environments and non-CVR environments. The project was approved by the University of South Australia's Human Research Ethics Committee (protocol number: 201739). In this section, we will describe the experiment in detail.

3.1 Conditions

There were two presentation conditions in this experiment: 1) Monitor condition and 2) CVR condition. Participants watched 3D computer-generated animations on a traditional 2D monitor in the Monitor condition and a HMD in the CVR conditions. The Monitor condition provided participants with a non-immersive watching experience where they sat in front of a traditional screen and watched 3D animations played on the screen. The CVR condition provided participants with an immersive watching experience where they watched 3D animations by sitting in the virtual environment of the 3D scenes.

We attempted to address the issues identified by previous studies (see Section 2.2) when designing the conditions. Firstly, we applied two restrictions on the experiment design to avoid the extra visual information that could affect participants' mental effort (as suspected by Rizzo et al. [50]): 1) we asked participants to not move their head (i.e. point of view) to the best of their ability in both conditions; and 2) we applied the same field of view in CVR and non-CVR conditions. We also controlled the position of the actions within events in the 3D computer-generated animations to be in front of viewers. The above methods allowed us to control the virtual cameras so that participants were exposed to the same content in both conditions. We still allowed participants to perform slight head movements to support a natural watching experience in both conditions; however, these slight head movements did not introduce any extra visual information besides stronger depth cues. Secondly, to evaluate the suspicion of MacQuarrie and Steed [38] regarding the quantity of participants, we tested more participants by applying a within-participants design, where 32 participants experienced each condition. Conditions were counterbalanced across participants.

3.2 Hypotheses

We proposed that the fully immersive watching experience of CVR could enable participants to perform a higher level of visual attention in a CVR condition than that of the Monitor condition. Secondly, following the suspicions of Rizzo et al. [50], we proposed the high level of engagement in CVR could enhance viewers' recall, if we avoid the possible extra mental effort brought by the extra visual information. Furthermore, emotions have been shown to strengthen people's attention and memory, and VR environments have been proven to provoke emotional responses (see Section 2). In our study, we also proposed that scenes that arouse emotions could enhance participants early visual attention and recall, and the effects of emotion would be stronger in CVR projects. As such, our hypotheses are as follows:

H1 Participants in the CVR condition will show better early visual attention as compared to that of the Monitor condition.

H1.1 Participants with negative and positive emotions will show greater early visual attention in each condition as compared to that of neutral emotions.

H1.2 Participants with negative and positive emotions in the CVR condition will show greater early visual attention as compared to participants with same emotions in the Monitor condition.

H2 Participants will show significantly better recall performance in the CVR condition as compared to the Monitor condition.

H2.1 Participants with negative and positive emotions will show better recall performance as compared to that of neutral emotions in each condition.

H2.2 Participants with negative and positive emotions will show better recall performance in the CVR condition as compared to participants with same emotions in the Monitor condition.

3.3 Animation Creation

As stated earlier, our experiment assessed visual attention and recall across negative, neutral, and positive emotions. We built up these emotional tones by differing virtual environmental elements such as lighting. We will introduce the creation of our virtual environments in this section, followed by the creation of the animated events.

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(a) Negative environment (b) Neutral environment (c) Positive environment

Figure 2: Example scenes of the virtual environment with different moods applied in our experiment.

Table 1: Animation Information

Animation Forms / Emotions	Fixed Position	Dynamic Position
Negative	Interior (84s), Park (102s), Street (105s)	Park (134s), Street (204s)
Neutral	Interior (99s), Park (93s), Street (86s)	Park(143s), Street (124s)
Positive	Interior (79s), Park (126s), Street (121s)	Park (229s), Street (164s)

Numbers in brackets indicate the length of the each animation

3.3.1 Virtual Environment

In our work, we generated three types of VEs (i.e. interior, street, and park). Guided by prior mood induction studies (as introduced in Section 2.4), we induced three types of mood (i.e. negative, neutral, and positive mood; expecting to arouse viewers' corresponding emotions) for each VE by providing different sounds, lighting effects, and environmental objects. Specifically, for the negative environment, we applied dark lighting and made the VEs cluttered; for neutral environment, we applied a neutral lighting effect and did not edit the VEs; for positive environment, we applied the bright lighting effect and imported pleasant environment objects (e.g. flowers). Different audio was also applied for arousing different emotions: noisy construction sounds were applied for negative environment, no sound was applied for neutral environment, and bird calls were utilized in the positive environment. Finally, we had nine types of VEs applied in the study (see Figure 2).

3.3.2 Animated Events

To maintain the fairness of the comparison between the animations, we generated the same number of events shown in each 3D animation (six), with all events occurring in front of the viewers. Each event contains a series of actions of 3D characters or objects. In order to avoid the impact of events' varying complexity on recall, we tried to ensure that all events maintained equal levels of comprehension. However, there were no complexity measurements applied in our study. To counterbalance the effects of 3D models and animations on emotion evoking and recall, each video was designed to have approximately the same number and type of models. In addition, in order to investigate the multitude of ways to present 3D computer-generated content in CVR, we also generated two kinds of 3D animations for each environment: 1) fixed position animations (i.e. viewers watch the events by sitting in a single position); 2) dynamic position animations (i.e. viewers were moved automatically to where the events would happen). However, because participants in our pilot study stated they felt significant VR sickness when being moved in the interior environment, we decided to remove interior dynamic animations from our experiment. As such, the final set of animations used 15 unique 3D computer-generated animations, of varied length (as illustrated in Table 1).

Figure 3: An example event: a dog walks out from a door, lies down, gets up, and runs away

3.4 Methods

We applied a within-participants experimental design, where each participant experienced both display conditions across the fifteen 3D computer-generated animations. In order to avoid learning or fatigue effects from the order in which animations were presented, we generated four different lists of animations by MIX [56], according to which a participant watched either seven or eight unique 3D computer-generated animations in each condition. The applied four lists consist of two sets, each of which contains two opposite lists. To illustrate, animation one is assigned to the Monitor condition in list one but it is assigned to the CVR condition in list two. Therefore, emotions, scenes, and animation types (i.e. fixed position and dynamic position) were equally distributed in CVR and Monitor conditions for even-numbered participants. The order of the conditions was also counterbalanced for each participant. After finishing both conditions, participants were asked to have a 20 minute rest. Participants then completed a recall test. In this section, we will introduce our experimental method in detail.

3.4.1 Participants

There were 32 participants in our experiment. Students, university personnel, and members of the general public were recruited. Participants were aged from 19 to 39 years old (M = 26.25, SD = 5.16; 10 males and 22 females). They were compensated with a $40 AUD gift card for their time.

3.4.2 Experiment Apparatus

In both conditions, the same computer (MSI VR One) with an Intel Core i7 processor, GTX 1070 graphics card, and 16 GB RAM was employed. In the Monitor condition and recall task, a 24-inch monitor with a 1920×1080 resolution was utilized. To minimize variance in response due to distance from the screen, all participants were seated at approximately 1 meter from the screen. In the CVR condition, participants watched 3D computer-generated animations using a Vive Pro HMD with a 2880×1600 resolution (1440×1600 pixels per eye). The settings of the virtual cameras in Unity were the same between conditions. The interpupillary distance was measured and set for each participant. For audio, a Lupuss LPS - 1520 headset was used in the Monitor condition and the built-in headphones of the Vive Pro were utilized in the CVR condition. The volume was the same between conditions for each participant. An Xbox controller was used in the recall test to capture input from the user.

EEG was employed to record participants' cortical response when they were watching 3D computer-generated animations in both conditions. A BrainAmp DC (Brain Products GmbH, Gilching, Germany) with 32 active Ag/AgCl electrodes mounted in an elastic cap (Brain Cap, Brain Products GmbH, Gilching, Germany) was applied. Electrode placement followed the 10/20 system. All electrodes were grouped into left anterior (F3, F7, FC5), mid-anterior (FC1, Fz FC2), right anterior (F4, F8, FC6), left central (C3, CP5, T7), mid-central (CP1, Cz, FP2), right central (C4, CP6, T8), left posterior (P3, P7), mid-posterior (O1, Pz, O2), right-posterior (P4, P8). EEG data was recorded with a sampling rate of 500Hz. All electrodes were referenced to FCz during recording, and later re-referenced offline to the linked mastoids. The electrooculogram (EOG) was recorded from the outer canthi of the left eye and below the right eye. Electrode impedance was kept below $5k\Omega$.

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3.4.3 Measurements

For EEG data, epochs for ERPs were segmented 200ms before and 1200ms after the onset of stimuli (an onset of stimuli was set at the start of an event), using a baseline of the -100 to 0 ms time window. Epochs for time frequencies were segmented 1000ms before and 2500ms after the onset of stimuli, without any baseline correction. For each participant, there were 90 epochs for ERPs and time frequencies respectively. For ERPs, based on the previous literature (as discussed in Section 2.3.1), we defined the time-window for C1 as from 40ms to 150ms, and the N1 time-window as 160ms to 210ms. We calculated mean amplitudes for the C1 and N1 time-window for each participant, each electrode over the posterior scalp (i.e. P7, P3, Pz, P4, P8) and each stimulus. Mean amplitudes that were larger or smaller than +-20 uV were removed as outliers. We quantified the ERP patterns by fitting the mean amplitudes of each time-window into Linear Mixed Effects Models (LMMs). We defined the main effects as *condition* (CVR: Monitor), *laterality* (left: midline: right), and *emotion* (negative: neutral: positive), and random effects as *participant number* and *stimuli number* (*animation ID*). In addition, we conducted Type II Kenward-Roger test to estimate the effect sizes (χ^2) and p values for each main and interaction effect. For alpha power, we calculated the mean power of alpha within the first two seconds after the onset of stimuli. The frequency range was individually adjusted, based on the individual alpha frequency calculated for each participant. Specifically, we first calculated Individual Alpha Frequency (IAF) for each participant using resting state EEG data (eye closed), averaged between before and after the testing session. Python-MNE package was applied. Then, the frequency range of the alpha band for each participant were determined based on IAF. Finally, we calculated the alpha power for each participant, each event, each time-window. LMMs was applied: we defined the main effects as *condition* (CVR: Monitor), *laterality* (left: midline: right), and *sagittality* (anterior: central: posterior), and random effects as *participant number* and *stimuli number*.

In order to avoid the possible electrical interference caused by the VR display and ensure good-quality EEG signals, the following literature-based methods were applied in our study: 1) To apply a sufficiently fast sampling rate [5]: we applied a rate of 500Hz (as introduced above), which can filter out electronic interference from monitors (60Hz to 70Hz) and VR displays (the Vive Pro has a refresh rate of 90Hz); 2) To apply the proper pre-processing methods for raw EEG data [17]: we imported the raw EEG data into MNE Python [25]. The Independent Component Analysis (ICA) was conducted to identify artefact components and reject these from the signal. We then filtered the data by a band-pass filter from 0.1Hz to 30 Hz; 3) To reduce possible biological interference from participants (e.g. body movements, noises, and discomfort with equipment) [46]: we applied a series of approaches including asking participants not to move to the best of their ability, running the study in a quite room with only a participant and a researcher, and limiting the length of each study phase within about 20 minutes to reduce participants' tiredness and discomfort.

SDT was applied to measure recall. Ninety short animations presenting old information and ninety animations showing new information were generated and employed. Animations containing old information were recorded from the 3D computer-generated animations that participants watched, including all the events (without background environment and audio tracks) that have been presented. We applied models and movements with the same quality to generate animations of new information.

3.4.4 Procedure

The experiment for each participant followed the same procedure:

Pre-experiment: The researcher introduced the experiment to participants, including study content and matters needing attention (i.e. the discomfort of using EEG and not to move to the best of their ability during watching animations). If participants agreed to participate, they signed the consent form. Then, researchers setup 32 electrodes, including eye electrodes, mastoid electrodes, and the EEG cap electrodes. In addition, the distance between pupils was individually measured and the VR headset calibrated accordingly.

Learning Task: Participants were introduced to the learning task in detail by viewing a slideshow presentation. They then experienced the two conditions. The order of the conditions varied for each participant in order to counterbalance. Before watching the 3D computer-generated animations in each of the conditions, we gave participants a practice session for the condition they were about to experience. Animations presenting 3D computer-generated moving cubes were applied in the practice session. After each of the animations, each participant was asked to rate the emotion levels of the animation by reporting a score from -10 to 10 (very negative to very positive), in order to confirm participants really experienced different emotions. The learning task was about 40 minutes long and each condition was about 20 minutes.

Between-tasks: Participants had 20 minutes rest between the learning and recall task, during which they were asked to finish a demographic questionnaire regarding the experience of VR.

Recall Task: Participants watched 180 short animations, each of which displayed one event. Participants needed to indicate if the played event was old or new. The results were recorded for SDT analysis. It needs to be mentioned that although we applied different environment objects and audio for differentiating the emotional tones of 3D computer-generated animations, the visual information applied in recall tests excluded environment and audio. Therefore we acknowledge that the emotion controls did not affect participants' recall performance.

Table 2: Results of the LMM (C1)

	chi^2	df	Pr($>chi^2$)
Conditions	17.67	1	<.05*
Laterality	0.42	2	0.81
Emotions	0.53	2	0.77
Conditions : Laterality	0.32	2	0.85
Conditions : Emotions	15.95	2	<.05*
Laterality: Emotions	1.14	4	0.89
Conditions: Laterality: Emotions	1.38	4	0.85

* indicates significance

3.5 Results

We applied ANOVA and paired t-test to compare participants' emotion ratings. The results showed that there were significant differences between our three types of emotional animations: negative animations ($M = -4.28; SD = 3.89$) compared to neutral animations ($M = 0.74; SD = 4.12$), $t(316.89) = -11.23$, $p < 0.05$; negative animations ($M = -4.28; SD = 3.89$) compared to positive animations ($M = 2.48; SD = 3.74$), $t(317.56) = -15.86$, $p < 0.05$; neutral animations ($M = 0.74; SD = 4.12$) compared to positive animations ($M = 2.48; SD = 3.74$), $t(315.1) = -3.95$, $p < 0.05$. The results confirmed that participants experienced different emotions as expected. There was no significant interaction between emotions and conditions ($p = 0.25$).

3.5.1 Brain Activities

Early visual attention: We examined ERP to evaluate early visual attention results. Figure 4 showed the grand average ERP for the early visual components during the learning task. Overall, stimuli presented in CVR elicited larger ERP negativities in both time windows. Results of the LMMs are displayed in Table 2 and Table 3.

In both C1 and N1 time-windows, we found a significant interaction ($p < 0.05$) between conditions and emotions. The interaction

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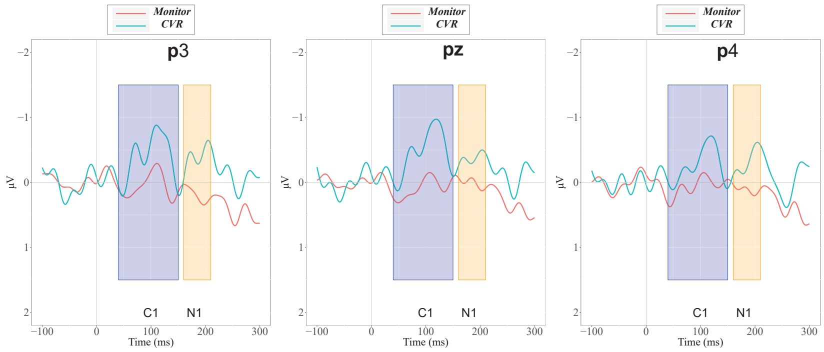
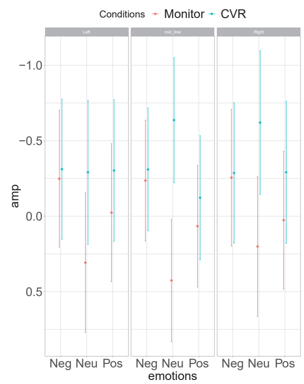
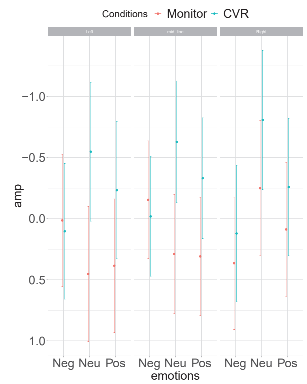


Figure 4: ERP results of posterior scalp for the first 300ms after the onset of stimuli, with C1 time-window (40ms to 150ms) and N1 time-window (160ms to 210ms). From left to right: "P3", "Pz", "P4". The y-axis reflects the amplitudes within the first 300ms after the onset (negativity is at the top). The results illustrate that stimuli in CVR elicit larger ERP negativities in C1 and N1 time-windows, which indicates greater early visual attention.



(a) C1



(b) N1

Figure 5: The interaction between emotions and conditions in the posterior region. The y-axis reflects the mean amplitudes within the time-windows: C1 (a); N1 (b). Negativity is at the top. Error bars reflect the predicted mean with 95% confidence interval. "Neg" refers to negative emotions, "Neu" refers to neutral emotions, and "Pos" is positive emotions. In both time-windows, the substantial negativity can be observed in neutral scenes. However, this effect is marginal in the positive and negative scenes. It reveals that the CVR condition is associated with higher early visual attention, however only in neutral scenes.

Table 3: Results of the LMM (N1)

	chi^2	df	Pr($>chi^2$)
Conditions	17.51	1	<.05*
Laterality	1.22	2	0.54
Emotions	0.45	2	0.80
Conditions : Laterality	0.17	2	0.92
Conditions : Emotions	12.74	2	<.05*
Laterality : Emotions	5.95	4	0.20
Conditions : Laterality : Emotions	2.04	4	0.73

* indicates significance

plot is shown in Figure 5. As illustrated, the CVR condition is associated with significant enhanced negativity (H1 was supported). This effect is marginal in the positive and negative conditions, but substantial in the neutral condition. To illustrate, viewers in CVR condition showed significantly higher early visual attention as compared to that of Monitor condition with neutral emotions; however, the difference is marginal when participants experienced positive and negative emotions (H1.1 and H1.2 were not supported). It should be noted that after C1 and N1 time-windows, a difference between conditions can be observed on Figure 4. While this difference provides evidence of a later effect, an investigation of the effect is beyond the scope of this work's intent and is not focused in this paper.

Alpha power: Figure 6 shows the grand average alpha power for nine example channels (C3, Cz, C4, F3, Fz, F4, P3, Pz, P4). The results of LMMs are displayed in Table 4. As illustrated, participants in the CVR condition showed significantly higher alpha power than that of the Monitor condition. In addition, the results also showed significant effect of brain regions (i.e. sagittality and laterality), and the significant interaction between conditions and brain regions.

Table 4: Results of the LMM (Alpha power)

	chi^2	df	Pr($>chi^2$)
Conditions	1468.93	1	<.05*
Sagittality	2601.51	2	<.05*
Laterality	371.89	2	<.05*
Conditions : Laterality	41.95	2	<.05*
Conditions : Sagittality	50.79	2	<.05*
Sagittality: Laterality	124.74	4	<.05*
Conditions: Sagittality: Sagittality	7.48	4	0.11

* indicates significance

3.5.2 Recall

After counting the number of *Hit* and *FA* according to SDT, we then calculated the value of d' for each participant, with the R *Psycho* package [39]. The descriptive statistics for d' is shown in Table 5. As the d' values for all the participants were normally distributed, a repeated-measures ANOVA was applied. However, there was no significant difference between conditions ($p = 0.70$; not supporting

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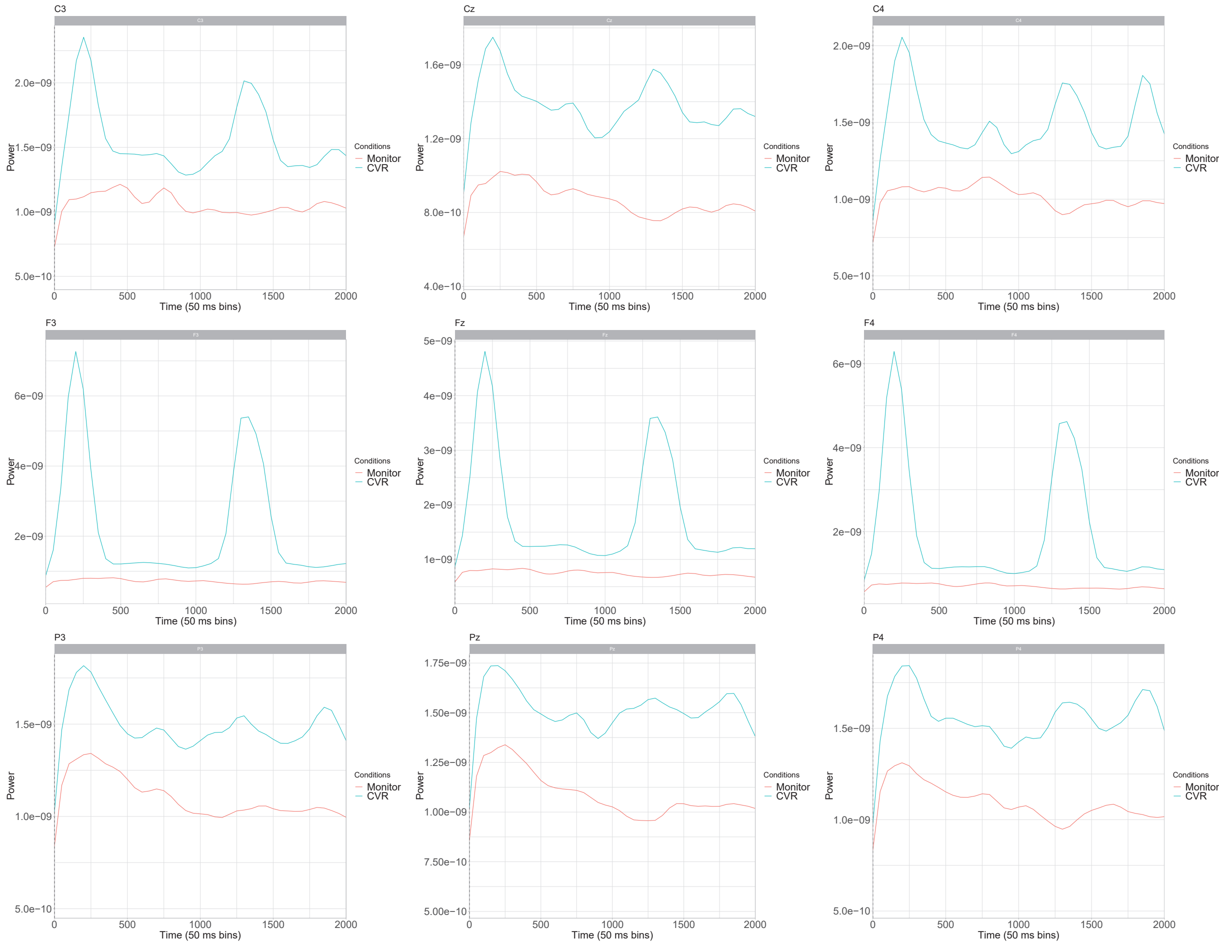

Figure 6: Alpha power for example channels: "C3", "Cz", "C4", "F3", "Fz", "F4", "P3", "Pz", "P4". The y-axis reflects the amplitudes within the first 2000ms after the onset of stimuli (negativity is at the bottom). Stimuli in VR elicited larger alpha power in all channels.

Table 5: Descriptive Statistics of d'

	Mean	Std. Error	Std. Deviation
CVR: Negative	2.44	0.18	1.03
CVR: Neutral	2.44	0.15	0.83
CVR: Positive	2.29	0.15	0.85
Monitor: Negative	2.37	0.16	0.89
Monitor: Neutral	2.66	0.14	0.79
Monitor: Positive	2.34	0.16	0.93

H2). There was no significant interaction effect between conditions and emotions (p = 0.95; not supporting H2.1 and H2.2).

4 Discussion

Our work examines the neuro-physiological effect brought by CVR techniques and reveals some potential benefits of CVR applications. At the same time, given the exploratory nature of our work and the lack of relevant literature, we recognized a number of issues when applying the EEG methodology and interpreting the EEG data in a CVR context. In this section, we will first conclude our findings and present our insights, and then discuss the issues we faced during the experiment and hope to shed some light on the future work in this domain.

4.1 Findings and Insights

We arrange our findings as follows: early visual attention, recall, and alpha power.

4.1.1 Early Visual Attention

Our results indicate that the CVR condition is associated with enhanced early visual attention. This effect is significant when viewers experience neutral emotions, while it is marginal when viewers have positive and negative emotions. Although it requires further experiments to specify the reason, we propose that the fully immersive watching experience presented by HMDs possibly enable CVR applications to introduce few-to-none distractions, and therefore participants could be highly engaged and focused on the content in CVR conditions, as compared to Monitor conditions. However, to our surprise, the attentional drawing effect of CVR and emotions does not appear to promote each other and the effect of CVR was possibly overridden by emotions in our positive and negative scenes.

4.1.2 Recall

Our results showed that the use of CVR does not affect viewers' recall of the visual information in 3D computer-generated content. Some possible explanations include: 1) The format of media (i.e. 2D monitor and CVR) are not associated with memory encoding; 2) The visual information of our 3D computer-generated content was very salient, which was possibly not complex enough to differentiate participants' memory encoding in different environments; and 3) Participants' first-time exposure to the techniques could account for the results. According to our survey, all of our participants were new to VR, therefore it is possible that they focused more on VR's novelty, and not on the visual information. As such, users might perform differently after greater exposure in VR and CVR. Again,

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this requires more studies to confirm.

4.1.3 Alpha Power

We measured alpha power for early exploration. According to our results, we found that the CVR condition showed significantly higher overall alpha power. According to previous literature, this result likely indicates a lower mental effort and/or an active inhibition (as introduced in Section 2.3.2). There are two potential interpretations for this: 1) it could be easier for viewers to process the visual information of 3D computer-generated animations presented in CVR (resulting in a lower mental effort) than on 2D monitors; or 2) when participants watched 3D computer-generated animations in the CVR condition, the neural excitability was better reduced and the interference processing was avoided (resulting in an active inhibition) as compared to that of the Monitor condition. Given the results and insights together with our experimental design (as our participants did not perform any tasks but instead passively watched animations) we believe the first interpretation is better supported. While the interpretation needs to be further examined to specify the reasons of the overall higher alpha power, in either interpretation, the overall higher alpha power in CVR is likely to reveal its benefits.

4.2 Exploring EEG measures for CVR

In order to measure early visual attention, we applied ERPs as a validated EEG measure. The use of ERP requires a clear onset point for differentiating the stimuli and non-stimuli phases, and therefore measuring participants' cognitive processing elicited by the events. However, animations (both 2D monitor and VR) generally consist of continuous imagery sequences, and therefore do not always have a clear onset point of single events. As a result, ERP measures at this stage would be difficult to be directly applied to general animations. In our work, we designed our 3D animations to show a series of single events that have relatively clear start and end points, and therefore, our events are all simple and salient. Our paradigm cannot measure the effect of complex animations and CVR applications that consist of continuous events and narratives. Further studies are required to develop suitable methods for testing animations and CVR applications of complex events and actions.

Regarding the results' interpretation, in addition to the overall higher alpha power in the CVR condition, we observed numerous spikes (as can be seen from Figure 6). One of the possible explanations is from the research of alpha oscillations; peaks of alpha power are likely aligned with selective attention [51]. Given our results, this literature suggests that viewers of CVR might be able to better focus on the objects in the presented 3D animations. The novel nature of CVR presentation could account for increased selective attention. As this novelty wears off, it is possible that the spikes in alpha would decline. This speculation, however, needs to be further examined. Following this, potential experiments include: 1) a study of alpha power and CVR with experienced users of VR and CVR techniques in order to examine whether the novel nature of CVR presentation causes these spikes; 2) to record the visual content that each participant consume in each condition as reference when analyzing and interpreting alpha power in order to investigate whether there are specific visual content that causes spikes. In addition, the significant difference between brain regions in the results of alpha power (as can been seen in Table 4) is another interesting indicator for the potential direction in the examination of CVR projects. Researchers have presented that different brain regions may be associated with different functions such as audition, auditory and visual recognition [19]. Our results followed that different brain regions acted differently when people watched visual information (both in VR and 2D screen). Future experiments focusing on specific factors (e.g. audio and visual) should be conducted with EEG recordings. This will help researchers understand the influencing factors and the involvement of cerebral regions as humans watch CVR applications.

5 Limitations

Our results indicate that CVR technologies could affect viewers' cognitive performance differently as compared to traditional monitors. We acknowledge that we did not specify the affecting factors in our experiment. Specifically, participants' different performance could be a result of different display types (i.e. HMD and monitor) or different presentation format (i.e. stereoscopic and monoscopic). However, we cannot address this question based on our experiment design. Further experiments to examine the affecting factors of CVR are necessary. Additionally, keeping participants' head stationary removes a very important feature of CVR (i.e. free movement); we acknowledge that this restriction applied in our experiment could reduce the level of immersion in CVR condition and therefore possibly influence participants performance. Following our initial exploration, work investigating CVR when viewers are allowed to move is required. Finally, the length of animations applied in this study is relatively short, as compared to the length of normal videos and film. When watching longer CVR applications, viewers might experience severe issues such as fatigue and motions sickness, which could affect their performance such as visual attention. Therefore, our results should be examined by applying longer CVR applications.

6 Conclusions and Future Work

In this paper, we evaluated the effect of CVR on viewers' cognitive activities. A user study was conducted, which compared viewers' cognitive activities between watching 3D computer-generated animations in non-CVR environment and CVR environment. Participants' behavioral responses of recall and cortical response were recorded. Significant differences were observed in cortical response, while there was no significant difference in the results of recall. Specifically, we found: 1) participants had better early visual attention in the CVR condition with neutral emotions, as compared to the Monitor condition; 2) participants showed higher alpha power in the CVR condition compared to Monitor condition, suggesting a lower mental effort and/or active inhibition is associated with CVR, as compared to viewing the same content on a traditional 2D monitor. These preliminary findings indicate the potentials of CVR to assist viewers regarding the consumption of visual information.

Research and analysis of CVR is still in its infancy. Following the work presented in this paper, we have an initial understanding of CVR, which can influence future research directions. Firstly, as suggested in Section 5, to study CVR when viewers are allowed to move is necessary. However, how to design such studies remains unknown. One of the questions is how to avoid the bias of different content when viewers are allowed to move their point of view in CVR conditions. Our future work will address this question. Possible experiment settings include 1) do not add any extra content in CVR environment (e.g. only showing the content in front of viewers and keeping the rest of the environment to be dark in CVR conditions); 2) recording the content captured by virtual cameras in CVR conditions and play it in Monitor conditions; 3) applying techniques such as VR portals [16] to limit the content that viewers can see in CVR conditions and keep the level of immersion. Secondly, as an initial investigation, we only studied general positive and negative emotions without specifying each emotion (e.g. fear and joy). In the future, investigations with specific types of emotions are needed. Such work could help to trace the effect of different emotions and reveal the applicability of CVR in specific emotional environment.

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