THE INFLUENCE OF 3D VIDEO ARTIFACTS ON DISCOMFORT OF 302 VIEWERS

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ABSTRACT

Today, numerous movies are produced in stereoscopic format. Despite the improvement in stereo technology, stereoscopic artifacts that cause headaches and other viewer discomfort continue to appear even in high-budget films. Existing automatic quality-control algorithms can detect distortions in stereoscopic images, but they fail to account for a viewer's subjective perception of those distortions. We propose a method of automatic subjective quality evaluation that uses technical parameters of stereoscopic scenes. It is based on subjective scores and brain-activity measurements using electroencephalography (EEG) to assess viewer discomfort. We conducted a series of experiments with active and passive stereo cinema technology. An audience of 302 participants watched 60 video sequences from stereoscopic movies containing artificially added geometric, color and temporal artifacts. Our analysis of the data revealed the dependencies between the degree of viewer discomfort and the intensity of the distortions. Scenes with temporal mismatch between the stereoscopic views caused the most discomfort among viewers. Future work will focus on creating models based on this data and using them to predict audience discomfort caused by watching stereoscopic movies.

Index Terms— 3D movies, stereo-video quality, fatigue, discomfort, headache

1. INTRODUCTION

Headaches, fatigue and eye strain make stereoscopic 3D cinema unattractive to many viewers. The authors of [16] interviewed 854 individuals who watched 3D movies in theaters. They identified several groups of symptoms; the most frequent were eye strain, blurred vision and a burning sensation in the eyes. A major reason for viewer discomfort is the presence of distortions in a stereoscopic image. For example, although one camera can rotate relative to the optical axis or shift vertically relative to the other camera during stereoscopic shooting, our eyes cannot do the same; therefore, these shots make the brain analyze impossible situations. Even high-budget films, such as *Hugo (2012)* and *Pirates of the Caribbean: On Stranger Tides (2011)* contain scenes with geometric and color impairments between the left and right views [14].

The most reliable way to avoid such distortions is to control the stereoscopic-content quality during production. But movie budgets and schedules seldom allow correction of all such artifacts, meaning noticeable distortions that cause viewer discomfort may remain. Recently, several methods for automatic quality evaluation of stereoscopic video have been proposed [15]. The frequency and intensity of an artifact, however, sometimes fail to represent how painful it can be for the viewer, and correcting it takes a considerable amount of time and money. Therefore, when controlling stereoscopic-video quality during production, it is important to consider subjective perception and to correct the most egregious distortions first. Eliminating these distortions will thereby reduce the number of spectators experiencing headaches and other discomfort while watching 3D movies, even if some artifacts remain.

The ultimate goal of our research is to predict the discomfort level a viewer will experience when watching a particular fragment of the stereoscopic video, using information about its technical quality. The first step toward achieving it is to conduct a series of experiments in which viewers estimate the discomfort they experience when watching stereoscopic scenes with artifacts; this paper describes these experiments and their results. We conducted experiments of two types. The first aimed to acquire objective information about a viewer using electroencephalography (EEG), which allowed us to estimate the viewer's level of fatigue. The second involved participants rating their fatigue level in a questionnaire. To obtain reliable estimates of discomfort, including responses from viewers with disordered binocular vision, we asked a large number of people to take part in this second type of experiment. The second step is to build the model using the data and rate the captured stereoscopic movies in accordance with the audience's discomfort level. In this paper we present a simple linear model; improving it and applying it to measurement of stereoscopic-movie quality is a subject for further research.

2. PREVIOUS RESEARCH

Viewer discomfort from watching stereoscopic video has many causes. They include low content quality (stereoscopic artifacts, unnatural distortions caused by 2D-to-3D conversion and so on) as well as failure to observe recommendations for comfortably watching stereoscopic content (poor display equipment and viewing from outside the zone of comfort, for example). Headaches and other discomfort can result from the high load that unnatural stereoscopic video puts on the human visual system. This situation leads to the vergence-accommodation conflict, which has been widely discussed in the literature [10, 11]. Since a major project for our research group is objective evaluation of stereoscopic-video quality [12], we wanted to measure and model the effects of such video on viewers. Thus, our investigation studied the artifacts that are characteristic to stereoscopic shooting.

The development and accessibility of stereo technologies has contributed to broad study of this field. Our work began with an analysis of Wei Chen's PhD thesis [2]. Chen described in detail types of stereoscopic artifacts and their impact on viewers. He conducted an expert assessment of the discomfort viewers experienced while looking at various distortions in stereoscopic images, and he also used EEG to compare two- and three-dimensional videos. His work revealed a correlation between the viewer's discomfort and the magnitude of geometric and other artifacts in a stereoscopic video. The authors of [1] used EEG to compare the effects of 3D and 2D movies on viewers, analyzing different brain rhythms and their combinations. These works, however, only assessed the general state of viewers before and after watching stereoscopic content; they did not investigate the dependence of fatigue on the technical characteristics of stereoscopic videos.

A deeper look into the causes of 3D-video-driven discomfort requires a detailed analysis of dynamic video features. The authors of [6] studied how motion in the salient areas of a scene affects viewer comfort. They considered vertical, horizontal and motion along the z-axis. Even though the models did not take into account camera movements, they revealed that viewer discomfort increases for scenes with a high speed of motion along the z-axis [3]. The task of assessing viewer discomfort using stereoscopic-video parameters has been widely considered in the literature, but only a few efforts devoted their experiments to analyzing stereoscopic-image distortions that are specific to stereoscopic filming. For example, [7] considered the influence of geometric artifacts on discomfort level, but the experiments only used stereoscopic images. The authors of [5] considered 22 distortion types, including geometric and color distortions. They did not, however, investigate temporal shift between the views, and the geometric distortions they added were uncharacteristic of stereoscopic shooting.

3. EXPERIMENT SETUP

Our work involved a series of experiments to obtain information about viewers' perception of various stereoscopic artifacts. We asked the participants to assess their discomfort level while viewing a specially prepared stereoscopic film, which consisted of video fragments with different artifacts of various intensities. An electronic questionnaire recorded the answers, with participants evaluating their discomfort level from 0 to 4 (where 0 indicates "no discomfort" and 4 indicates "strong discomfort"). They each evaluated their discomfort at a specific time after every stereoscopic scene. At the beginning of the experiment, we showed the viewers examples of video fragments containing stereoscopic images without distortion and with strong distortion. These examples gave the viewers context for evaluating scenes during the experiment.

For several reasons, we decided against also showing 2D versions of the scenes. First, many recent works [1, 8] have investigated fatigue accumulation in viewers who watch 2D compared with those who watch 3D movies. Second, conducting the experiments with so many participants is difficult; we focused more on obtaining information about stereoscopic-artifact perception. Second, it is hard to conduct the experiments with such a large number of participants, and we were focused more on receiving information about stereoscopic artifacts perception. To reduce the impact of earlier video fragments on the perception of later fragments, we showed participants the same stereoscopic film with the video fragments in reverse order. The total duration of each experiment was 39 minutes.

A similar experiment employed EEG, except it involved verbal questionnaires (because the use of electronic devices can distort EEG recordings and because the viewing room was dark, the presenter asked participants five times during the film how they felt). The duration of each experiment was 60 minutes. EEG recording was continuous throughout the prepared stereoscopic film.

3.1. Videos

For our experiments we prepared 60 video fragments (each 30 seconds long) from four full-length captured stereoscopic movies: *Hobbit: An Unexpected Journey (2012)*, *47 Ronin (2013)*, *Prometheus (2012)* and *Stalingrad (2013)*. Our selections included scenes with different movement, depth and brightness dynamics (Fig. 1). None of the video fragments contained significant distortions. We artificially added to them four types of stereoscopic artifacts that are typical of stereoscopic filming (Fig. 2). Twenty video fragments contained two different distortion types. Each distortion had one of five intensity levels from 0 to 4, where 0 indicates no distortion and 4 indicates severe distortion. We chose the intensity of each distortion in accordance with the distribution of its appearance in the full-length feature films (Fig. 3), en-
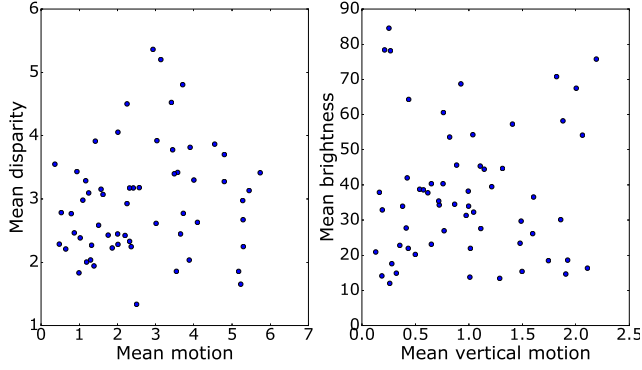
Fig. 1: Scatterplots of temporal and spatial parameters for selected video fragments. The left scatterplot shows the average motion-vector length in pixels (*x*-axis) versus the average absolute disparity in percent of image width (*y*-axis). The right scatterplot shows the average vertical-motion-vector length in pixels (*x*-axis) versus the average brightness (*y*-axis) on a scale from 0 to 255.

(a) Color mismatch   (b) Scale mismatch

(c) Rotation mismatch   (d) Temporal shift
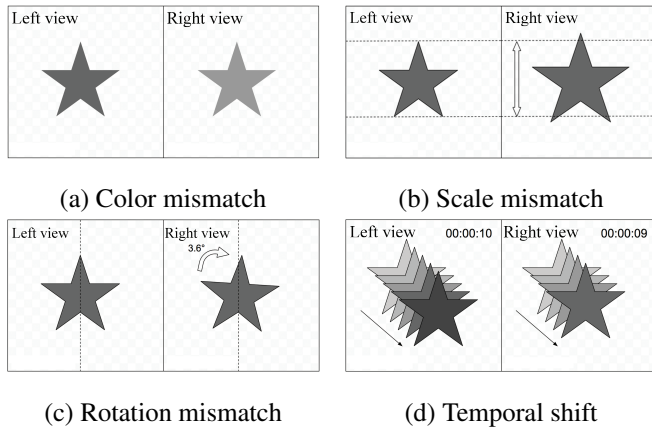
Fig. 2: Schematic visualization of stereoscopic-image artifacts.

suring it had a sufficient magnitude to make it noticeable to viewers. The red lines in the figure mark the 80th, 95th and 99th percentiles, each representing the respective percentage of frames in 60 captured stereoscopic movies that exhibit lower intensity for that distortion. The prepared scenes appeared in balanced random order (no scene was preceded or followed by another with similar artifacts, and the aggregate distortion intensity was distributed as evenly as possible over the test film). The film is conditionally divisible into three main parts. The first part contained 20 videos in which all those from the same movie had the same type of distortion (e.g., scenes from *47 Ronin* all exhibited color distortion of various intensities). The second comprised scenes that varied in artifact type and power, and the third comprised scenes with two types of distortions (note that zero intensity means the distortion is absent; some scenes therefore included only
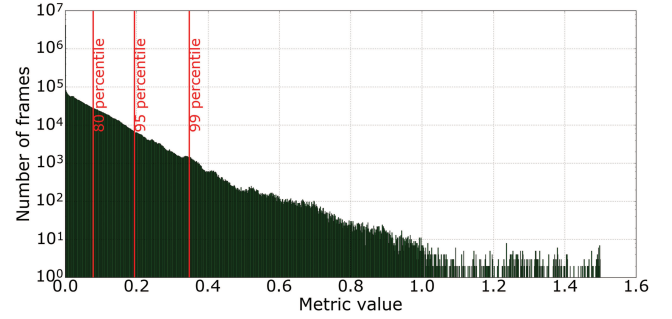
(a) Rotation of one view in degrees (*x*-axis) versus number of frames (*y*-axis, logarithmic scale)
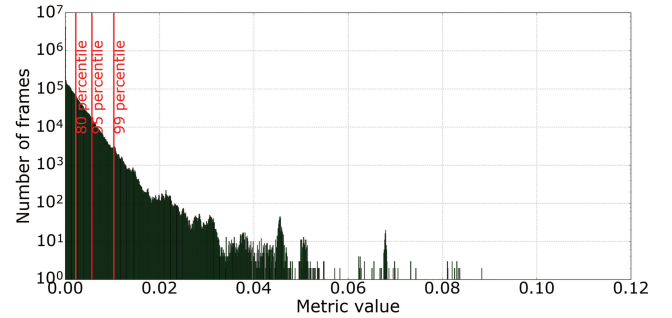
(b) Ratio of scale mismatch between views (*x*-axis) versus number of frames (*y*-axis, logarithmic scale)

Fig. 3: Histograms showing the number of frames containing an artifact of given intensity in 60 full-length captured stereoscopic movies.

one type of distortion). The x-axes in Fig. 9 shows the order of the scenes in the test film.

3.2. Subjects and equipment

For our subjective experiments, 302 subjects participated, 112 watched the test film with the video fragments in normal order and 258 watched it in reverse order (68 watched the test film twice). Thus, we received a total of 370 responses for each distorted scene. Of the participants, 30% were female. The ages of all participants ranged from 18 to 42 years, with an average of 20. We conducted the experiments in an auditorium equipped with two Digital Projection Titan 1080p-700 professional projectors with linear polarization. The resolution of each projector was $1,920 \times 1,080$. The screen had a silver coating and a diagonal of 9 meters. Fig. 4 is a photograph taken during one of the experiments.

We conducted an experiment to measure brain activity in a specially equipped room provided by the Movie Research Company and Neurotrend, employing an active-shutter 3D system. The experiment used a B-Alert X24 professional electroencephalograph, with the electrodes placed according to the 1020 scheme. The room was noise-insulated. In ad-

Fig. 4: Subjective experiment in progress (photo brightness artificially increased).

(a) Participant waiting for the electrodes to stabilize (b) Participant ready to start the experiment

Fig. 5: Preparation for an experiment using EEG.

dition to the EEG data, we also recorded eye-tracking, polygraph and webcam data. Eight subjects took part in these experiments. Fig. 5 shows photographs of two participants before the experiment.

4. EEG ANALYSIS

Our analysis used a Fourier transform with a Hanning window to obtain a time-frequency representation of the EEG signal:

$$F(m, \omega) = \sum_{n=-\infty}^{\infty} f[n]\omega[n-m]e^{-i\omega n}, \qquad (1)$$

where m is the width of the window, ω is the window function and $f[n]$ is the value of the discrete function (signal) with argument n. We used the Hanning window for the window function:

$$\omega(n) = 0.5 \cdot (1 - cos((2\pi n)/(N-1))) \qquad (2)$$

Because a 50 Hz frequency (interference induced by the power grid) dominated the signal, we applied a bandpass filter from 0.1 to 49 Hz (Fig. 6). We calculated the power-spectrum
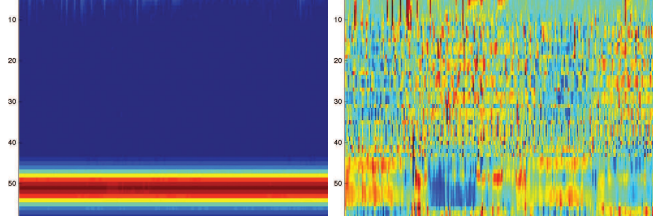
(a) The 50 Hz frequency strongly predominates (b) Spectrogram after filtering

Fig. 6: Spectrogram of an EEG signal before and after suppressing the 50 Hz frequency. The y-axis (inverted) represents the frequency and the x-axis represents time, where one count corresponds to 1/1,024 seconds.

density (PSD) of the signal for each channel (Fig. 7):

$$PSD(k) = \frac{|F(k)|^2}{N^2}, \qquad (3)$$

where k is the measurement number, $F(k)$ is the complex amplitude of the sinusoidal signal (the result of the Fourier transform) and N is the signal length.
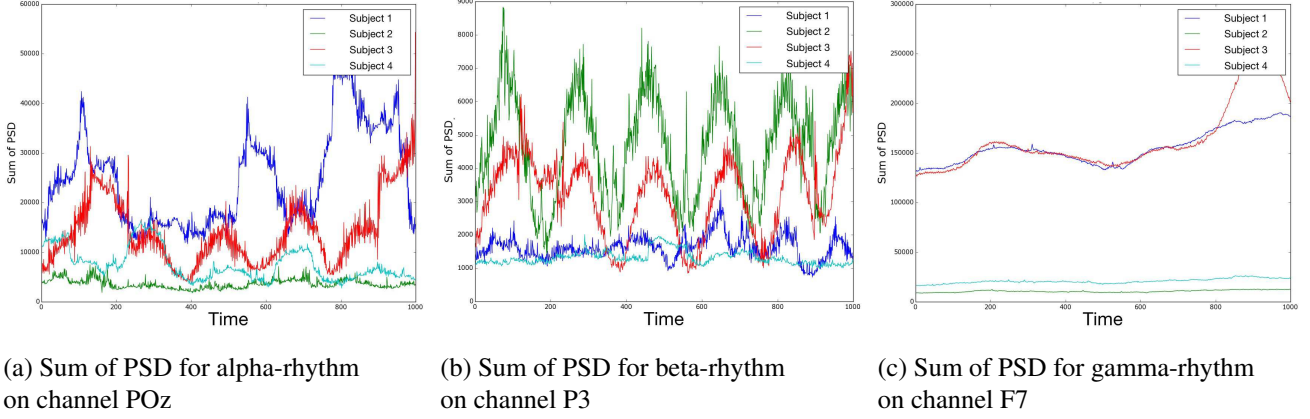
To account for the contribution of each brain-rhythm frequency, we summed the PSD for all frequencies in each rhythm. Several frequency bands are associated with certain types of brain activity [9]:

- 1-4 Hz — delta rhythm (usually associated with the deep-sleep phase)

- 4-8 Hz — theta rhythm

- 8-13 Hz — alpha rhythm (registers during calm wakefulness, especially with the eyes closed, but is blocked or weakened by increasing attention or mental activity)

- 13-30 Hz — beta rhythm (characteristic of the REM sleep, and when the subject is solving complex verbal problems)

- 30-50 Hz — gamma-rhythm

The next step was to calculate the entropy of the rhythms. The author of [4] used this approach for the initial EEG data. For this paper, we calculated the approximate entropy of the brain-rhythm PSDs using the following algorithm:

1. Identify source signal: $u_1, ..., u_n$

2. Form vectors: $x_1, ..., x_{N-m+1}[x_i - u_i, u_{i+1}, u_{i+m-1}]$

3. $\Phi_m(r) = (N + m - 1)^{-1} \cdot \sum_{i=1}^{N-m+1} log(C_i^m(r))$, where C_i^m is the number of x_j elements that satisfy the condition $d[x_i, x_j] < \frac{r}{N-m+1}$ and r is a predefined parameter

(a) Sum of PSD for alpha-rhythm on channel POz

(b) Sum of PSD for beta-rhythm on channel P3

(c) Sum of PSD for gamma-rhythm on channel F7

Fig. 7: Total power spectral density of brain rhythms as a function of time. Each line corresponds to one subject.

### 4. Approximate entropy: $\Phi^m(r) - \Phi^{m+1}(r)$

We recorded EEG data during the entire experiment, but at several points we asked participants to simply rest with their eyes closed (doing so allowed us to minimize interference in the collected data). The experiment included five such instances: once before we showed the test film, once after and three times during pauses in the film. We applied our algorithm to the signals and compared the results with subjective scores that participants provided after each rest time. The results revealed that the degree of discomfort is best estimated by the characteristics of alpha and beta rhythms. The Pearson correlation coefficient is 0.93 (p-value = 0.02) for the alpha rhythm on channel POz. This study used automatic 3D-video quality metrics [15] to find and measure stereoscopic distortions; these metrics have frame-level accuracy. Unlike the questionnaires, EEG also enables measurement of viewer discomfort for each video frame. Our method can help refine assessments based on questionnaires that evaluate fatigue.

5. RESULTS

The use of EEG technology allows us to track changes in the subject's mental state with high temporal resolution, but it requires too many experimental sessions to construct a representative data set. Moreover, objective indicators of fatigue in EEG data is a controversial topic owing to the complexity of brain activity and the numerous external factors that affect both the state of the subject and the recording of data. The EEG approach applies to simple tasks: for example, those with static stimuli and those involving a general assessment of the viewer's state. Our task requires reliable estimates of viewer discomfort for complex stimuli (scenes from feature movies containing several artifacts). This effort ultimately aims to predict the state of average viewer, requiring numerous participants. Therefore, the results of subjective experiments are more useful in our case; at least, the questionnaires make it easier to reliably estimate viewer discomfort.

Before watching the test stereoscopic video, participants were asked about their preferences for watching movies in theaters. Of the participants, 31% prefer 2D format, 59% watch both 3D and 2D movies, and only 10% prefer 3D format. Before and after the experiment, all were asked to notice any negative physical reactions to the video. Table 1 shows how many participants experienced different reactions. Only half of them suffered no negative response after watching the test video; a noticeable percentage felt headaches and/or eye pain. Participants also had the opportunity to indicate the presence of any other reaction – the most popular ones were nausea and dizziness, but some noted intensification of hunger or other negative sensations they felt before the experiment. Fig. 8 shows the distribution of participants' aver-
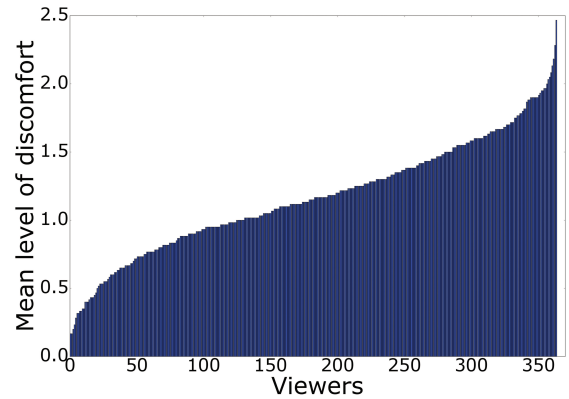

Fig. 8: Ordered average estimates of viewer discomfort (*y*-axis) versus viewer (*x*-axis).

age discomfort level during the entire experiment. It shows that only a few responded with high or low ratings; the others ranged from 1 to 1.5. We combined the responses for the normal order and reverse order of the test video sequence and calculated confidence intervals for each scene. Fig. 9 shows these confidence intervals, where each column corresponds

Table 1: Number of participants who noted negative physical reactions before or after the experiment.

	No negative reactions	Drowsiness	Fatigue	Headache	Eye pain	Other reactions
Before viewing	203 (70%)	70 (24%)	51 (18%)	8 (3%)	11 (4%)	8 (3%)
After viewing	114 (40%)	74 (26%)	112 (39%)	45 (16%)	94 (33%)	17 (6%)

(a) Scenes with one distortion

(b) Scenes with two distortions
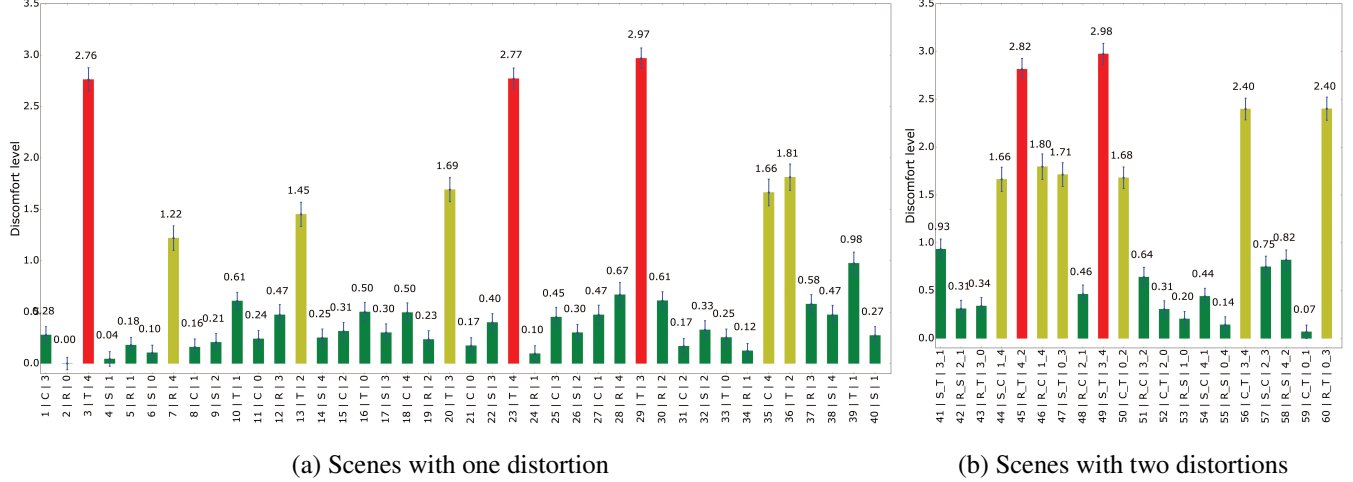
Fig. 9: Average viewer discomfort for scenes with different distortions of various intensities. Here, C is color mismatch, R is rotation mismatch, T is temporal shift and S is scale mismatch. The distortion intensity is in the range from 0 to 4, where 0 means no distortion.

to the MOS (mean opinion score) of participant discomfort while watching a given scene. The scenes are arranged in the order they appeared in the forward video sequence. Scenes marked in red caused participants the most discomfort; green corresponds to a low discomfort level. The most discomfort came from video fragments with a large temporal shift between the views, as well as scenes with two distortions. Table 2 shows average scores for participant discomfort when viewing scenes with different artifacts. The upper part of the table represents the numerical values of added distortions; the bottom part represents the average participant discomfort when watching scenes containing a given distortion. Participants noted the greatest discomfort for scenes with a temporal shift between the stereoscopic views. They experienced similar discomfort for scenes with geometric distortions, but at the high end of scale-mismatch intensity, the level of discomfort stayed relatively constant. This effect is because the bigger distortions that result from achieving such a high intensity are indistinguishable to viewers. For some distortions, the increase in discomfort with increasing artifact power is not monotonic. The reason is the presence of other factors that influenced each viewer's response, such as scene parameters (motion, depth and brightness), progressively increasing viewer fatigue, the viewer's position relative to the screen, and the viewer's visual and other characteristics. Thus, development of a model that takes these parameters into account requires further study of their effect on visual discomfort. We

measured all these features in our experiments and plan further analysis to improve the model.

The table also contains percentiles of distortion intensity. For example, the 95th percentile means 5% of frames contain distortions of even greater intensity (the statistics are based on the 60 full-length captured stereoscopic movies), and the viewer will experience the same or worse discomfort when viewing them.

(a) Linear model

(b) GBR model
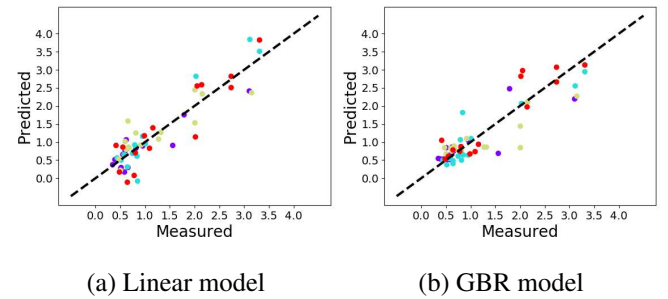
Fig. 10: Accuracy of model predictions on cross-validation test samples (each color refers to one cross-validation test split). The *x*-axis represents the measured audience discomfort; the *y*-axis represents the model's prediction.

We trained simple models (linear regression and gradient-boosting regression, or GBR) on our data set. The accuracy in Fig. 10 is for fourfold cross-validation; each color represents the corresponding test splits. Table 3 shows R-square

Table 2: Participant discomfort for scenes containing various distortions.

	Distortion type	Distortion intensity			
		1	**2**	**3**	**4**
Characteristics of stereoscopic artifacts in video sequences	Color mismatch (MSU-3DColor-2011)	15	40	110	160
	Percentile	82.06	95.00	99.15	99.55
	Rotation mismatch	0.3°	0.6°	0.9°	1.2°
	Percentile	98.38	99.85	99.98	99.99
	Scale mismatch	100.5%	100.8%	101%	101.3%
	Percentile	99.34	97.87	98.87	99.55
	Temporal mismatch	0.1 frame	0.3 frame	0.5 frame	0.6 frame
	Percentile	97.61	99.38	99.69	99.75
Total assessment of participant discomfort	Color mismatch	0.65±0.03	0.58±0.03	0.70±0.03	1.42±0.05
	Rotation mismatch	0.47±0.01	0.75±0.03	0.86±0.03	1.28±0.04
	Scale mismatch	0.49±0.03	0.61±0.02	0.69±0.03	0.70±0.03
	Temporal mismatch	1.13±0.04	1.97±0.04	2.67±0.05	3.10±0.04

Table 3: Model coefficients of determination and mean squared error (MSE) averaged on fourfold cross-validation splits.

	Train R^2	Test R^2	Test MSE
Linear	0.96±0.004	0.75±0.066	0.14±0.024
GBR	0.99±8.28 $* 10^{-6}$	0.74±0.057	0.15±0.036

scores averaged on cross-validation splits, as well as the average test mean squared error. The algorithms used data based on objective stereoscopic-video quality metrics developed by the VQMT3D Project [15], averaged over the scene, as well as their standard deviations for that scene. The labels are the average discomfort levels for the scene without any normalization by age, row or other individual parameter. As mentioned earlier, our future work will aim to create a model that takes into account individual-participant characteristics and that assesses the audience's average discomfort when watching a stereoscopic movie.

6. CONCLUSION

This research involved conducting a series of subjective and objective experiments to obtain information about viewer discomfort from watching stereoscopic movie scenes. These scenes contained artificially added distortions that are specific to stereoscopic filming. Our analysis revealed the dependencies between the discomfort level and an artifact's intensity. The analysis of brain rhythms revealed correlation between alpha- and beta-rhythm entropy and viewer discomfort. Comparison of distortions with equal intensities and equal frequencies showed that temporal shift between the stereoscopic views causes the greatest viewer discomfort. Even though this distortion is unnatural, it occurs in feature stereoscopic movies [13, 14]. We used the data we obtained to estimate the audience discomfort level for 60 stereoscopic movies. In ad-

dition to this data about viewer discomfort, we collected data about other features that could affect perception of stereoscopic video. Analysis of this information is a subject of further research.

To continue our work on this topic, we plan to classify participants by their susceptibility to artifacts in order to study accumulation of discomfort and to expand our assessment of discomfort caused by stereoscopic movies. For this effort, we will take into account the percentage of viewers susceptible to various distortions. We are also preparing new experiments involving other artifacts.

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