Communication Papers
Media Literacy & Gender Studies

CP, 2019, Vol.8 – No17, pp. 21/35 ISSN 2014-6752. Girona (Catalunya). Universitat de Girona. FAJNZYLBER, V.; WENNER, A.; MOYANO, J. SBERT, M.: From NPR to VR: tracking ocular behavior in immersive virtual reality. Recibido: 12/11/2019 - Aceptado: 14/12/2019

From NPR to VR: tracking ocular behavior in immersive virtual reality

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ABSTRACT

In this work, we present a research about ocular behavior during immersion in virtual reality. To enhance our comprehension of human behavior in immersive conditions, we will focus on vision and its reactivity to non-photorealistic rendering and cinematic procedures. Using physiological data collected in real time with an eye tracker, we compare attentional and pupillary response in order to describe the visual immersion experienced by the user. This proposal could be useful to identify physical sickness produced by perceptual mismatches and to evaluate the cognitive efficiency of virtual reality contents, giving feedback to producers about ocular behavior of users, in different fields of applications.

Keywords: "Eye tracking" ; "Non-photorealistic rendering" ; "Perception" ; "Virtual Reality"

1. INTRODUCTION

The field of immersive experiences could be defined as a transdisciplinary design area and development of various products that integrate technology and creativity, which contribute to the creation of experiences in various sectors. When talking about immersive technologies we refer to virtual, augmented and mixed reality, while video games are related to the concept of interaction. However, both technologies can be combined into immersive and interactive experiences.

Numerous film and audiovisual festivals in the world have created sections to disseminate audiovisual content produced with these technologies, however, after reviewing the editorial definitions of these exhibition instances, we realized that there is no global consensus on what truly defines this new generation of contents. Some define virtuality as an extension of existing means, importing narrative or interactive operations from the cinema or video games.

Lastly, the point of view that seems most open to us is the definition of virtual from the user's point of view. In order to clarify the contribution of our research we will begin by defining what we understand by immersion and how it relates to the processes of human perception.

2. RELATED RESEARCH

2.1. What do we understand by immersion?

In media studies, this concept is known as immersion. This word has its origin in the experience of 'diving into' an environment; that is to say, to enter and participate bodily in a new scenario, in a specific space-time. In a broader sense, this implies disregarding real-world references. And along with that, it allows to address sensations of reality that come from the new environment, created artificially by some means that seek - or perhaps not - the emulation of reality as we perceive it.

For experts, the concept of immersion has not reconciled a unique and invariable definition. And likewise, the concept has been correlated with other terms, has acted as a synonym for presence and has been known under other names (e.g. 'immersive presence ') [5].

The concept of immersion comes from the idea of experiencing full submergence in a given environment. In a field familiar with this term, such as virtual reality, it relates to the perception of feeling physically present in a simulated environment. Virtual reality conveniently provides input devices, with a degree of perception of self-movement, which allows the senses to be isolated enough to feel transported to another place.

Immersion materializes in unique experiences for the user, such as reading a book, comics, watching an audiovisual or musical show. Immersion is studied in different fields and a virtual reality experience may not be immersive. However, for the purposes of our field, immersion will be understood as the objective level of sensory fidelity provided by a virtual reality system [28].

That is, the ability of a simulation to approximate a real experience. For this, the sensations of the real world must be eliminated as much as possible, and replaced by the sensory experiences corresponding to those of the built virtual environment [24]. Presence, often correlated and at the same time confused with immersion, is understood as the subjective psychological response of the user to the simulation [28]. It is a cognitive and perceptual consequence of immersion, and if wanted, possibly the last phase of this, after the stages of commitment and absorption of the experience [3]. In simple terms, it corresponds to a hoax; the subjective belief that one is in a certain place, even when physically located in another [31, 26].

Hence, we cannot speak of immersion, and consequently, of immersive technologies without referring to the sensory and cognitive impact, ultimately, the bodily effect produced by these digital deceptions. Until now, the gradual realism of the experience seems one of the necessary conditions for the production of previous results. However, we consider it appropriate to specify the 'sense of realism'. On the one hand, we have 'perceptual realism', which is what we vaguely understand as 'realism' or 'photorealism': "how well the environment looks and sounds like the real world" [23]. And, on the other hand, social realism, the plausibility of a reality experience, regardless of the style of representation (e.g. the use of NPR in immersive environments) [10].

This condition of reality must be coupled with the technological means used. Virtual reality (VR) is perhaps the computer technology that, in essence, allows through head-mounted displays (HDMs), which cover the user's entire field of vision, the multimedia simulation of a fully immersive scenario. Today, it seems to us an almost natural system of interaction and control of the immersive experience, admitting a degree of perception of one's own movement, while at the same time, allowing the senses to be isolated enough to feel transported to another place (often confused with reality).

The use of VR, however, has been associated with certain discomforts; being unknown that the possibility that these annoying body manifestations were actually symptoms of increased immersion and/or presence in the face of experience [6]. Despite the enormous technological progress, problems of discomfort have been reported in users. They have been studied extensively by the academy, generating standardized metrics and procedures to assess these discomforts. And with this, improve the experiences to minimize these effects, which are mostly related to the depth of fields, experience control, color tone within the experience. This occurs in artistic-cultural content (films, games, educational experiences) as well as in those destined for industrial training of professional competencies.

VR experiences still produce physical discomfort because all the key elements of the associated physiological phenomena have not yet been deciphered, at least in the context of content producers. In other words, creators and engineers produce content without having methods or tools that allow them to evaluate the physiological impacts of their products. Many resources can be invested to build immersive experiences that produce collateral effects, without knowing well how to measure them to avoid them, except going through merely intuitive trial and error processes, without scientific basis.

Our research seeks to advance in the understanding of virtuality from user experience, that is, how people perceive their own experience of virtuality and, therefore, how the discomforts associated with current forms of immersion are experienced. Hence it is not possible to talk about immersive technologies without taking charge of the biophysical dimension of their effects on the user, because most of the experiences that are generated, in startups or audiovisual companies, are carried out without studying the sensory impact of its contents.

2.2. Biophysical dimension of immersive experience

3D cinema and VR share a series of similarities emphasizing first of all that both require binocular optical devices. They are also technologies that have expanded the areas in which they are used, such as cinema and museum exhibitions, and there is a massification to the point that they are beginning to enter, incipiently, into homes.

Both technologies use perceptual resources that stimulate multi-sensorially, which implies the use of more than one sense to increase the realism and immersion of the user. In most cases it is bimodal, that is, it occupies two of the five senses that in this case are visual and sound.

According to studies [21,14], vision is the strongest sense therefore the attention and position of objects in space are determined by the user's vision. For this reason, sound becomes a complement of the image. The above is known as the ventriloquist effect or visual capture effect where there is an impression that the sound originates from the object, a phenomenon similar to the performance of the ventriloquist and his doll.

When perceiving images and sounds from a virtual world it is possible that physical discomforts will be felt by the user, similar to those known as motion sickness, where the person may feel nauseous, dizzy, headaches or eye fatigue [29]. There is a precision in the name which depends on whether it is 3D, where it is known as 3D vision symptom and in VR visually induced motion sickness (VIMS).

These technologies simulate realities that engage perception, and this is where cue conflict is generated, known as one of the most accepted theories, which refers to the specific information received by the brain and the motor system from sensory stimuli. That is, cue is the way the body estimates its movement from perceptions. Therefore, if there is a disagreement between the stimuli and the body, the discomfort that causes the side effects mentioned above appears.

Other elements associated with the discomfort could be related to different factors of each individual where age, concentration, previous experience, gender, or diseases (physical or psychological) can influence. In addition, there are factors directly related to technology that could influence the user's physical feeling such as calibration, contrast, field of view, color, binocular vision, among others [19].

Given that the phenomenon of sickness in 3D or VR is not new, the physical discomfort tests have expanded to the point that it began as a subjective questionnaire that is still applied and today these studies count with medical devices known as the objective examinations. The objective tests include monitoring of breathing, heartbeat, eye blinking, body stability tests or the central nervous system from an electroencephalogram (EEG) [7].

The simulator sickness questionnaire (SSQ) consists of a questionnaire that distinguishes 16 symptoms in nausea, discomfort, disorientation and ocular categories, from a 4-point scale where 0 is nothing and 4 is severe. It is commonly used before and after 3D or VR technology to ensure that there are no pre-immersion symptoms [2].

In a study [29] they examined whether the cause of physical discomfort could be induced by exposure time and if the symptoms of VIMS worsened or changed with peripheral vision or the visual monitoring of an object. They used subjective and objective measurement methods to analyze users during the study. Among these they included the SSQ, body stability and near-infrared spectroscopy that measures without invading the body, the reactions of different activities in the cerebral cortex to the subjects in their natural state. They were able to conclude that sensory areas, such as vision, could be activated when using 3D.

3D cinema and VR share the problem of causing physical discomfort during the exhibition, affecting users and immersion experience. The difficulty is that when a user feels discomfort it is possible that there will be a reduction of immersion, directly influencing the user experience in a negative manner. Hence in these secondary symptoms, where the visual sense predominates, it can remove the person from their connection with photorealistic viewing, taking into account that longer exposure time generally increases 3D vision symptom and VIMS.

Each of these discomforts increases or decreases according to the user's susceptibility, as well as the exposure time or the delay between physical movement and its virtual action [19,1]. However, the emphasis on the influence of visual representation technique (e.g. non-photorealistic rendering) has not been properly placed.

2.3. Visual dimension of an immersive experience: photorealism and immersion

In computer generated images (CGI), we find two great methods of expression. On the one hand, photorealism (PR) and on the other, non-photorealism (NPR). The photorealistic rendering aims at the optical representation of the world, that is, the imitation of the physical principles of photographic capture, both on volumes, textures, shadows, as effects of color and lighting [9].

In contrast to the PR, non-photorealistic rendering gathers and designates a wide variety of creative and stylistic filters of digital processing, and is validated by it [18]. The NPR before the PR is considered more expressive and beautiful, as well as more efficient in the transmission of information and convincing in performance [14]. Therefore, it constantly has applications depending on the transmitted aesthetics and the ability of scientific visualization that this expressive range gives us [4].

This method (NPR) allows you to regulate the information in the visual file (image or video), either by subtracting attributes or by providing new features (e.g., the painting styles inspired by Van Gogh, Renoir and Dufy) [17]. Not satisfied with that, within the range of NPR, we find endless possibilities of resulting styles; as well as efforts to classify them according to the design characteristics and behavior of each technique, considering even the interaction with the user [20].

As we said, NPR has the ability to replicate an artistic style by abstracting the properties of the corresponding image or video [30]. Through this process there is not only a modification in style and content of interest, but also the attention and the way it is looked at. In other words, it modulates the perception of images by users, already recorded through questionnaires [13] and based on eye tracking data [27].

In fact, in previous studies, we have realized that the high level of abstraction could trigger in users: "a lower exploration of the scene and a greater focus on the more expressive elements of the scene bodies and faces of the characters" [8].

NPR, through the use of diverse styles, refers to different and significant user reactions. On the one hand, it is known that emotions are stronger in the face of photorealistic images. Instead, compared to stylized images, we have a more neutral state. Probably, this decrease in response in the transition from PR to NPR is not due to the loss of information itself, but it would be presumed that NPR eventually confuses and distracts users. Despite this, photo-abstractive processing, a visual format that reconciles the best of PR and NPR, preserves a very good emotional response [25].

Considering that immersion is a process that, under ideal conditions, should occur without physical discomfort, we will develop an analytical method that allows us to evaluate the importance of visuals in the origin of such discomfort. Our work plan is as follows: we will take the method used in the study of immersion in 3D cinema and adapt it to the study of virtual immersion, in order to evaluate how non-photorealism can modify the perception of content, and consequently, identify possible ways of solution to the discomforts of immersion.

Our hypothesis is simple: inferences about ocular behavior in 3D cinema, obtained through the use of eye-tracking, can be applicable to virtual reality in order to describe the ocular behavior, and to describe the immersion process of each user. The justification for this hypothesis is found in the understanding of human perception as an enactive process, that is, the human response to experiences comes mainly from their socio-historical experience. This implies that each user can combine different types of immersion, and what matters to us, rather than looking for universal patterns, is to be able to correlate the contents and visuals in order to identify the cognitive importance of the various objects of visual interest existing in the immersive content.

3. METHODS

We conducted an experiment with a total of 27 anonymous students in the city of Santiago (Chile): 14 women and 13 men, between the ages of 18 and 23, who voluntarily participated in this experiment, using informed consent. Subjects with visual pathologies were excluded to produce comparable ocular responses to audiovisual stimuli. To collect the data, a screening room was prepared with the "The Eye Tribe" eye-tracker mounted below the LG, LED 55 Full HD Smart TV 3D/55LB6500. The eye tracker was used at 30Hz, while the television was configured at a resolution of 1920 * 780 pixels.

3.1. Video processing

Video selection for the experiment: photorealistic 3D vs. non-photorealistic 3D. We edited a stereoscopic short film of 3 minutes and 30 seconds. This film was processed with a "pastel" filter from an NPR software prototype, extracting color and texture information in order to generate a monochrome non-photorealistic version of the video (black lines on white backgrounds).

We selected an NPR filter that can be perceived as a high degree of abstraction. We are aware of the influence of artifacts on NPR perception, as stated by Mould et al. [18] but we chose a not visually appealing NPR style, with visual artifacts, in order to explore a highly abstract aspect very different from the photorealistic sharpness typically used in 3D cinema. We wondered whether this perceptual efficiency associated with NPR could be obtained with a high degree of abstraction, but without affecting the immersive effect of the stereoscopic depth. We produced two videos in NPR mode and two videos in PR mode (photorealistic), example shots are shown in Figure 1. In total, we had four videos with the same duration.

3.1.1. Non-photorealism and visual abstraction

From a technical point of view, NPR methods can be classified into object-space methods and image-space (also called screen-space) methods [27]. For the purpose of our study, we decided to use a realtime processing technique based on a screen-space method, to evaluate the impact of this NPR filter, which seeks to produce a high level of abstraction, in order to induce cognitive uncertainty during the cinematic experience.

3.1.2. Sound post-production

Once the visual processing took place, we conducted a process of audio postproduction, which consisted of producing two different versions from the same audio material of the short film. The first post-production, deemed narrative, consisted of emphasizing the voices as the main element of the sound mix. The other post-production, deemed immersive, put all of the elements of ambient sound at the same level, including the voices of the characters as part of the total sound mix. The narrative sound was labeled S.N. and the immersive sound as S.I. In total, we generated two videos with narrative sound (S.N.) and two videos with immersive sound (S.I.), all with identical duration.

3.2. Experimental design and procedure

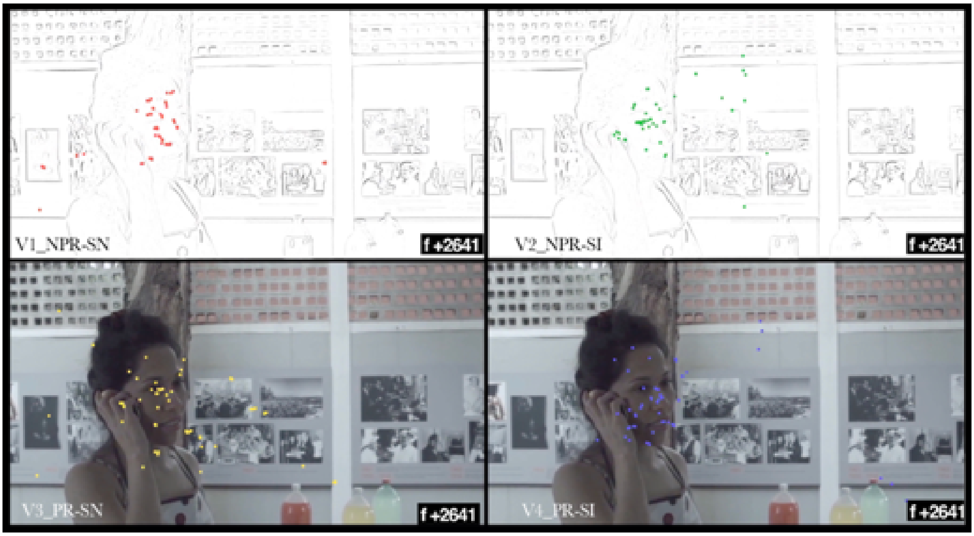
Combining both forms of film post-production, image, and sound, we generated a total of four videos, with identical duration. Table 1 includes the detailed contents of the videos.

Table 1. Image and sound postproduction setups used in our tests.

	Name	Visual style	Sound style
Video 1	NPR-SN	Non-photorealistic	Narrative Sound (dialogues)
Video 2	NPR-SI	Non-photorealistic	Immersive Sound (ambients)
Video 3	PR-SN	Photorealistic	Narrative Sound (dialogues)
Video 4	PR-SI	Photorealistic	Immersive Sound (ambients)

These videos were presented to the participants, and their eye movements were measured with an eye tracker (see Figure 1).

Figure 1: Four videos presented to participants.



Each volunteer watched the four videos using polarized glasses. The presentation sequence was varied to distribute the bias of seeing a film for a second, third, and fourth time. At the time of defining our experimental design, we did not have a previous hypothesis about how the gaze is affected simultaneously by the postproduction of image and sound. If our study had focused only on the visual factor of NPR, we could have used a between-subjects design. However, despite the small size of our sample, we used a within-subject design to open a possible future direction for experimentation and data gathering.

3.3. Data capture

The facilitator conducted a calibration phase with the eye tracker before presenting each video. The eye tracker generated for each (user, video) pair a text archive table with the columns timestamp, leftx, lefty, rightx, righty, pupilleft, pupilright. For this study, only the data for ocular focus was considered, leaving the data for pupil response for a future work.

3.4. Data processing

Once the data capture process was completed we proceeded to unify those records into a file useful for posterior analysis. The resulting dataset, containing identifiers for user, video, frame, and the coordinates of the point of interest (x and y). It was composed for 1,349,944 validated records with an average of 62.14 captures per frame.

In order to check if what the users watched was significantly different, we performed a generalization of Student's t-statistic used in multivariate hypothesis testing called Hotelling statistic test [15] present in R packet ICSNP, version 1.1-0. To do so, for each pair of videos (V1-V2, V1-V3, ..., V3-V4) and every frame, we tested the null hypothesis: what users are watching in video x and video y is the same.

We also measured if the post-production produces more dispersion or diversity in what the users watched. We use the Shannon entropy [22], as a measure of dispersion. Before computing those values, we converted our two dimensional variable, the coordinates of the point of interest, into a one dimension discrete variable. Both, entropy computing and variable transformation were calculated using the R entropy package, version 1.2.1.

3.5. Data analysis.

Once the data capture process was completed we proceeded to unify those records into a file useful for posterior analysis. The first step in transforming this data was to annotate the files generated by the eye tracker with a user identifier and a video identifier. After that we could merge all files into a single one. Then, we transformed the timestamp column into the corresponding frame of the video. To do that, we split the video frame by frame, using the FFmpeg utility. Afterwards, we filtered missing data and errors (data outside the monitor), and computed the average point of interest of both eyes.

Finally, in order to increase the number of observations per frame, the showings of frame i was included in frame i-1 and i + 1. The resulting dataset, containing identifiers for user, video, frame, and the coordinates of the point of interest (x and y). It was composed for 1,349,944 validated records with an average of 62.14 captures per frame.

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This data allows to statistically characterize the ocular response in terms of attentional behavior and pupillary reactivity, but we needed a qualitative approach to describe the audiovisual content, in terms that allow us to compare the 16 identified episodes. We make this qualitative description using two types of descriptors: cinematic procedures and cinematic events. On the one hand, we define cinematic procedures as those factors potentially present in any cinematographic content: editing cuts and camera movements. On the other hand, we define cinematic events as elements placed inside the filmed scene: fluctuations of characters and objects within the scenic space.

The quantitative description was also made with an additional criteria: pupillary reactivity as a marker of emotional response. Regarding the comparative analysis of pupillary reactivity data in the 4 videos allowed the identification of three sets of results. We observed significant differences in pupillary reactivity between PR and NPR videos. We analyzed the data to establish if there were possible correlations between the pupillary reactivity, the behavior of ocular fixations - described with the concept of entropy as a measure of attentional dispersion- and the temporal evolution of the film.

In summary, combining quantitative (attention, emotion) and qualitative criteria (cinematic events), we analyzed the data to establish if there are possible correlations between the audio-visual content and the observed ocular response. This allows us to analyze the ocular behavior in stereoscopic immersive conditions.

4. RESULTS

4.1. Attentional behavior: perceptual anxiety in non-photorealistic scenes

In general terms, NPR is associated globally with a lower visual entropy, that is, a greater gaze concentration on fewer areas of interest. Qualitatively we may observe two correlations: NPR is associated with a greater concentration in the faces and a lower exploration of the scenic depth.

Facing a non-photorealistic scene, characterized by a correlation between visual abstraction and cognitive uncertainty, the gaze seems to react under the effect of a perceptive anxiety: an ocular behavior that can be described as a limited exploration of the scene and a greater focus on the most expressive elements of the scene, such as bodies and faces of the characters. This behavior appears to us as an adaptive response to a visual environment endowed with abstraction and uncertainty. This perceptive anxiety seems to spontaneously assign greater sensorimotor resources to the analysis of the character's behavior, transforming his face into the main key to analyze the information and the emotional tone of the global scene.

NPR leads us to search in the faces the keys to infer expected behaviors and interpret the global scene. This seems to apply especially in contents whose coherence is guaranteed by the narrative centrality of the characters. But it could also be a good clue to explore the attentional behavior in virtual reality contents with 360 degree scenes, where the user is constantly invited to move their gaze to explore the scenic space.

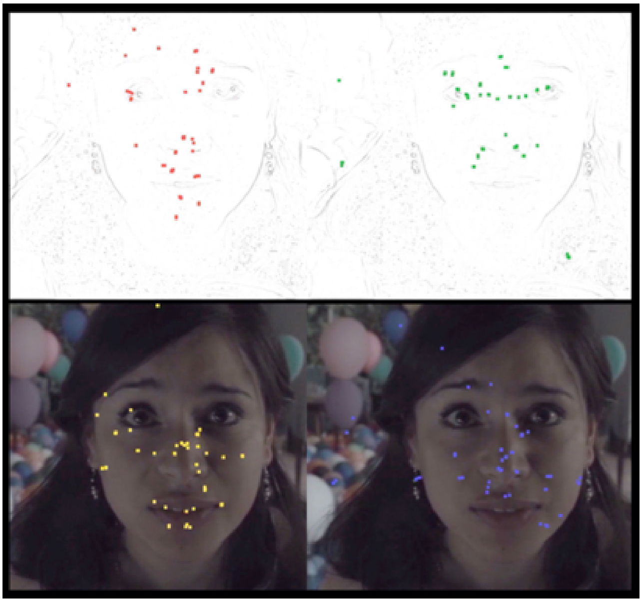
4.2. Pupillary reactivity: emotional immersion vs. intellective immersion.

The analysis of the pupillary reactivity observed in its temporality throws a concrete difference between photorealistic (PR) and non-photorealistic videos (NPR). In comparison with significative pupillary fluctuations observed in PR videos, the NPR filter used seems to produce a normalization effect pupillary reactivity to light fluctuations. This is confirmed by the light variance, which is much lower in NPR videos compared to PR videos. This tendency led us to expect that the pupillary reactivity would be determined by this lower light variance. However, we found a result that changes everything.

In the final scene of the film, we detected the largest area of differences in pupillary reactivity in the NPR videos: the whole scene is built around a character who performed a doubly significant action: at the same time that she developed a verbal discourse with an intensifying facial expression while she approached the camera (see figure 2). During her body movement towards the camera, the stereoscopic effect produces the illusion that her head emerges from the screen.

The ocular task of constructing the stereoscopic illusion of an emergent face is added to the intellective action of constructing an interpretation of the scene based on facial and vocal expressivity. This final scene is more visually complex than the previous ones and despite the subtraction of visual objects produced by the NPR filter, the pupillary behavior does not seem to be reacting only to light fluctuations. Considering the limited scope of our data, we cannot affirm that these differences correspond only to an emotional response, but it is clear that they do not seem to indicate a unique type of immersion.

Figure 2: Final scene of the film analyzed with eye-tracking data



The emotional response seems to vary depending on the type of visual style, although the evidence is not so strong in this direction, it is clear that the research carried out opens implications beyond 2D and 3D cinema: it helps understand cognitive complexity as a central factor to understand immersion. The case found in the final scene, where NPR videos present a greater pupillary response, could indicate a feature consistent with the evidence mentioned above: greater visual complexity could be correlated with greater pupillary response.

Then, everything is played between the space of the perceiving subjects and the type of visual style proposed. The gaze fluctuations (more entropic in PR videos than in NPR videos) may correspond with the corporal involvement indicated by the pupillary reactivity. Also, it could be inferred that when information is more dispersed, the intellective task of linking the sound treatment with the visual interpretation of the scene does not occur equally in PR and NPR videos. This led us to make the difference between a more emotional immersion, in NPR videos, than a more intellective immersion in PR videos.

5. DISCUSSION

The results obtained indicate that ocular behavior, described thanks to the use of eye-tracking, can be a useful source of information to describe immersion. When describing the evolution of the vision in relation to the temporal flow of the content, it will be possible to interpret the reactions of the users to the fluctuations of the characters and the scene.

The concept of perceptual anxiety could be useful in the context of 360-degree scenes, since it would identify the user's need to obtain the information necessary to interpret the meaning of each scene. Unlike the cinematographic montage, prepared before viewing, the head and body movements made by VR users constitute the new form of assembly. If we are able to characterize the perceptual functions of these vision movements, we can analyze the narrative and cognitive efficiency of a virtual reality content based on the user's eye behavior.

Combining the analysis of visual entropy (dispersion of the vision in the scene) with the emotional response, we will be able to have experimental evidence, subsequently verifiable through interviews, to discern how intellectual and emotional moments could alternate. There is no single type of immersion: each user travels the scenic space according to their own interests, but if we discover recurring patterns in the ways of seeing, we will have advanced another step towards the understanding of immersion in VR.

These inferences about vision were made possible by the experimental use of NPR. If we use these findings to assess the importance of visual factors in the occurrence of discomfort during virtual immersion, we can replicate the same method: evaluate whether the same virtual reality experience, operating with different visual styles, generates physical discomfort at the same times. The visual abstraction of the NPR seems to elicit different responses from the viewer of 3D cinema. If this is replicated in virtual reality, it would mean that postproduction, together with ocular analysis, could reduce or modify the negative effects of virtual immersion.

6. CONCLUSIONS

The comparative analysis of ocular behavior under different visual styles opens up new perspectives for the understanding of the concept of immersion. Attention and emotional vision markers can be used to implement an empirical method, based on eye-tracking data, to study immersion in virtual reality. In order to deepen this line of research, it will be necessary to adapt the methods of data analysis, for example, by incorporating quantitative methods of ocular data analysis to identify objects of visual interest in the three-dimensional space of immersive experiences. If we can correlate the way we see with what interests us in a scene, we can describe our immersion experience with greater precision.

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